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Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Wave Climate and Wave Response, Kawaihae Deep Draft Harbor, Island of Hawaii, Hawaii

Edward F. Thompson, Zeki Demirbilek, and Michael J. Briggs

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Final report

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ABSTRACT: Present and projected commercial activities in Kawaihae Deep Draft Harbor, Island of Hawaii, HI, indicate that a deeper basin and entrance channel and better protected berthing areas will be needed. The U.S. Army Engineer District, Honolulu, in coordination with the Harbors Division, Department of Transportation, State of Hawaii, requested numerical (computer) model studies in support of harbor planning. Wave climate incident to Kawaihae Deep Draft Harbor was developed from National Data Buoy Center directional buoy data. Numerical model STWAVE was used to modify the buoy data to account for significant differences in exposure between Kawaihae and the buoy locations. Numerical model CGWAVE, validated with field measurements for short waves (wind waves and swell), was used to: 1) evaluate the impact of deepening the existing harbor, which was found to be minimal; 2) determine optimum length for a proposed stub extending seaward parallel to the existing entrance channel from the tip of the existing breakwater; and 3) evaluate the technical feasibility of six alternative modifications to the harbor. Model results were compared to experience in the existing harbor and to general criteria for operational acceptability.

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Preface

This report describes procedures and results of a wave climate and wave response study for Kawaihae Deep Draft Harbor, Island of Hawaii, HI. The study was performed in support of long-range planning for the harbor. The study was performed by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), for the U.S. Army Engineer District, Honolulu (POH). The study was conducted during the period April 2003 through March 2006.

Mr. Thomas D. Smith, U.S. Army Engineer District, Honolulu, was the project engineer. Key meetings and visits during the study were the site visit on 31 October 2003; Project Delivery Team (PDT) meeting and technology transfer workshop at POH on 29 June 2005; and project review meetings at CHL on 4 November 2004, 2 March 2005, and 15 December 2005.

The investigation reported herein was conducted by Drs. Edward F. Thompson, Zeki Demirbilek, and Michael J. Briggs, all of the Harbors, Entrances, and Structures Branch, CHL. The final report was prepared by Dr. Thompson.

This study was performed under the general supervision of Mr. Thomas W. Richardson, Director, CHL. Direct supervision of this project was provided by Mr. Dennis G. Markle, formerly Chief, Harbors, Entrances, and Structures Branch (HESB) and Mr. Jose E. Sanchez, Chief, HESB.

At the time of publication of this report, COL Richard B. Jenkins, EN, was Commander and Executive Director of ERDC and Dr. James R. Houston was Director.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	meters
miles (U.S. nautical)	1.852	kilometers
tons (2,000 pounds, mass)	907.1847	kilograms

1 Introduction

Background

Kawaihae Deep Draft Harbor is one of two deep draft harbors on the Island of Hawaii. The harbor is located on the northwest coast of the island, approximately 50 miles[1] northwest of Hilo, the other deep draft harbor (Figure 1). Kawaihae Deep Draft Harbor serves the needs of a growing West Hawaii population and resort community as well as limited military operations.

Kawaihae Harbor is exposed primarily to waves approaching from the west, with the full exposure arc ranging from southwest to northwest. Waves can approach the harbor vicinity unobstructed from about 220-310° azimuth, but swell from more northerly directions experiences blockage by other islands in the Hawaiian chain. The harbor entrance channel is aligned with waves approaching from 300° azimuth. The stronger winds in the area typically come from about 50-100° azimuth. The 1-min average wind speed exceeded one percent of the time is about 10 m/s (20 knots) (Thompson 1992).

The harbor is protected by one 808-m (2,650-ft) long breakwater (Figures 2 and 3). Since the north end of the Island of Hawaii and other islands afford natural protection from energetic northerly waves approaching the Hawaiian Islands, the wave climate at Kawaihae is generally mild. The higher energy waves at Kawaihae are relatively long-period westerly swell, short-period seas generated by local winter storms to the southwest (called Kona Storms), and, rarely, hurricane-generated waves. The breakwater is armored with 8- to 12-ton rock. Breakwater construction was completed in 1962 and the structure has been maintenance-free. The harbor entrance is a 158-m (520-ft) wide channel between the breakwater tip and the coast. A coral reef extends along the exposed breakwater to the edge of the entrance channel and fringes the coastline north of the entrance channel. The reef adjacent to the breakwater is about 320-430 m (1,000-1,400 ft) wide. The slope from reef crest to 3.3-m (10-ft) depth is about 1:100.

[1] A table of factors for converting non-SI units of measurement to SI units is presented on page ix.

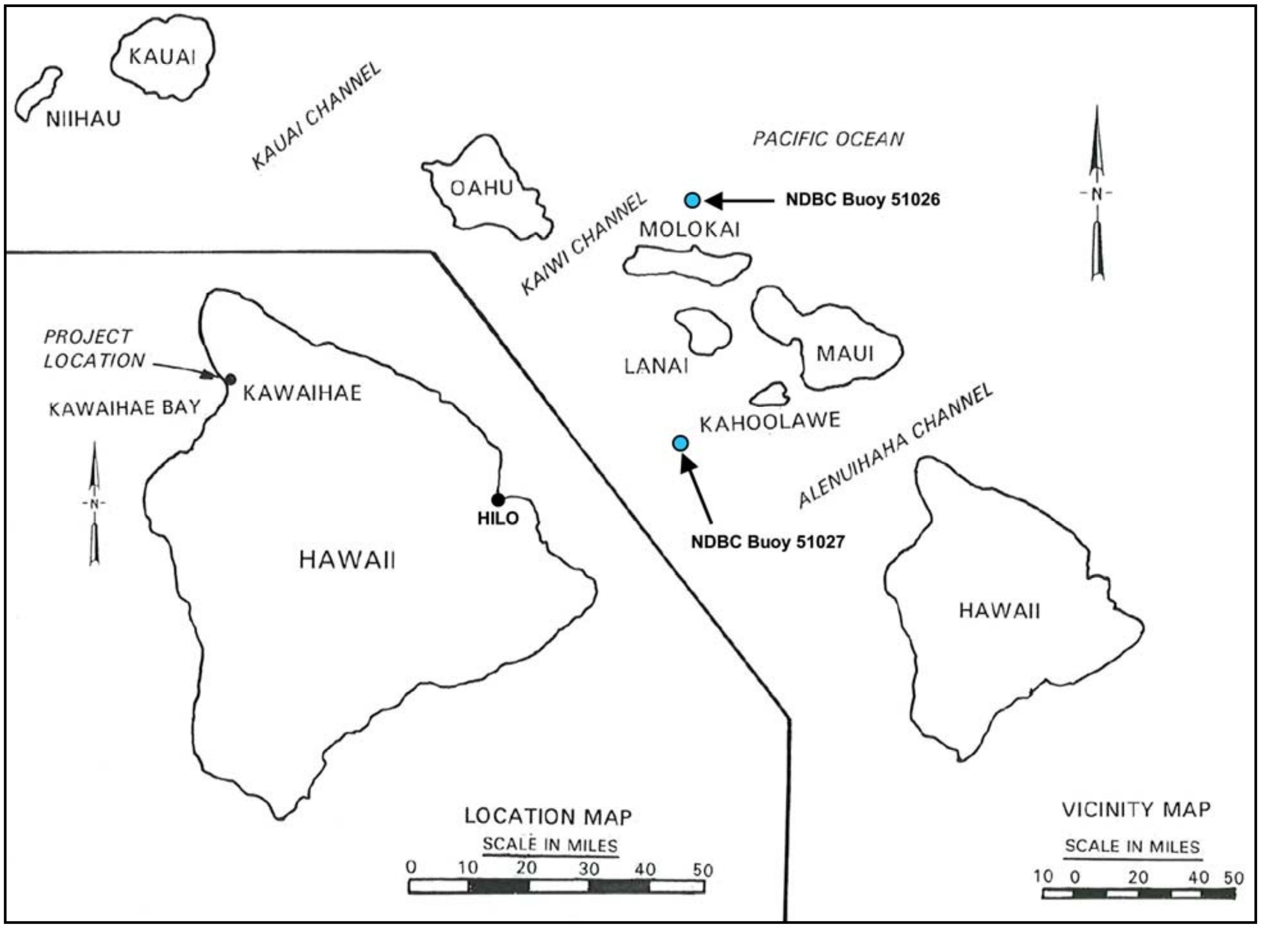

Figure 1. Location map of study area

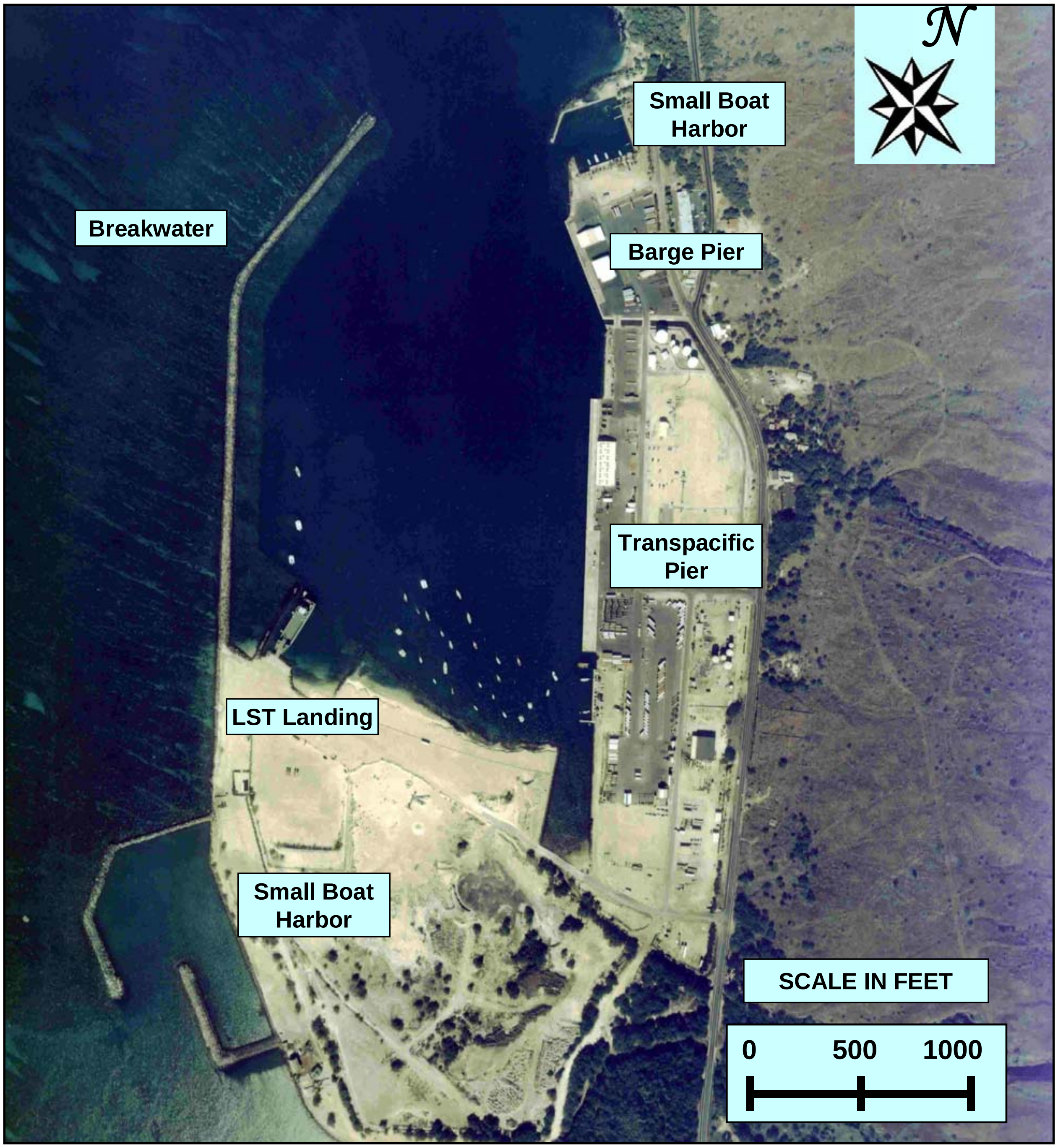

Figure 2. Kawaihae Deep Draft Harbor aerial photo, 17 November 1999

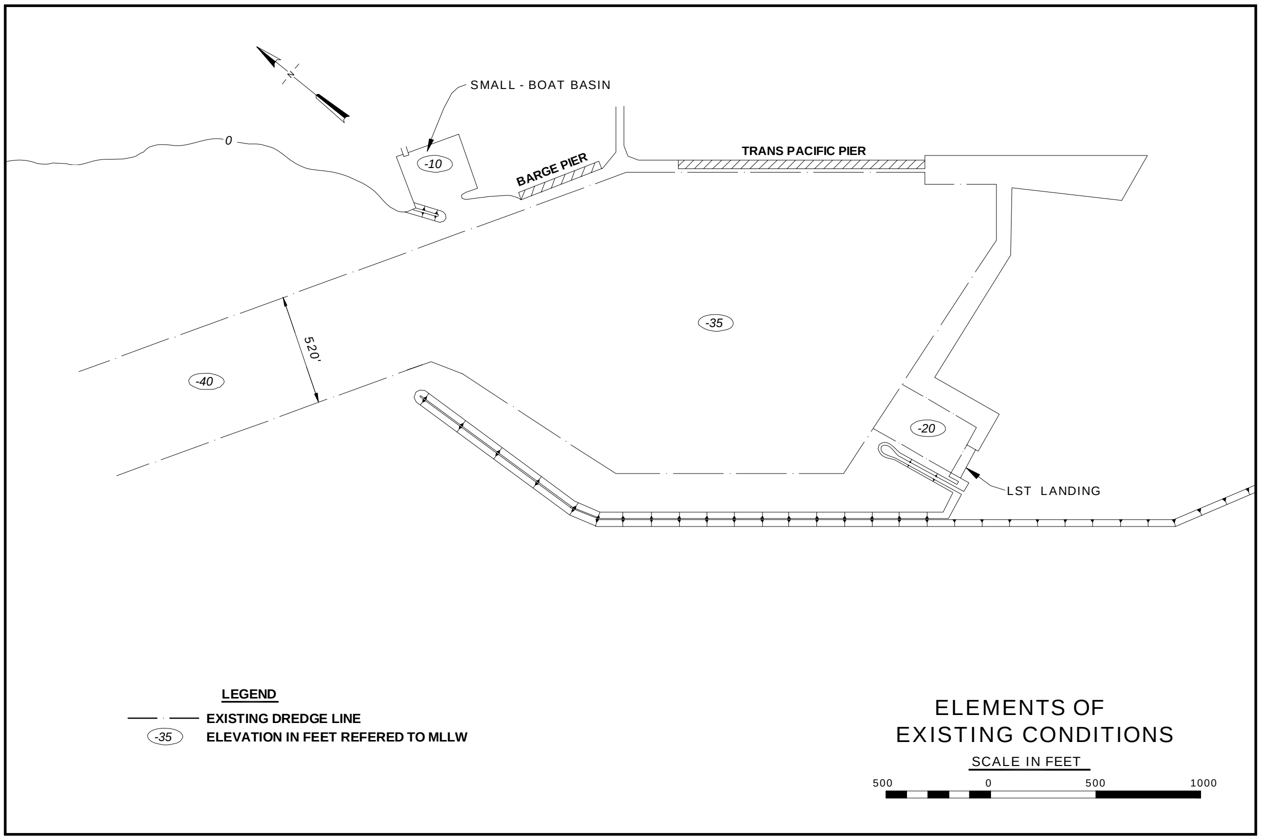

Figure 3. Kawaihae Deep Draft Harbor, existing plan

Commercial piers are located along the east side of the harbor (Figures 2 and 3). Piers are used by a variety of vessels including barges, commercial cargo ships, and tug boats. Pier 1, referred to as the barge pier in this study, is relatively exposed and receives limited use by barges and other traffic that does not produce heavy loads on the dock and apron. The primary dock area is referred to as the Transpacific Pier in this study. Water depth is 12.2 m (40 ft) in the Federal entrance channel and 10.7 m (35 ft) in the harbor basin and commercial pier areas.

A harbor facility designated as a U.S. Army reservation is located near the southwest corner of the deep draft harbor. This facility includes a small basin dredged to 6.1-m (20-ft) depth, is used by military Landing Ships, Tanks (LST), and other vessels, and is referred to as the “LST landing area” in this study. East of the LST landing, the harbor-land interface consists of a shallow beach. Shallow-draft vessels moor in open water at the south end of the deep draft harbor, just north of the beach area. Some dock facilities for shallow-draft vessels are available along the shore extending southeast from the Transpacific Pier. The harbor tail extending into the southeast corner is not routinely used.

A small boat harbor is located just northwest of the barge pier, including a short breakwater on the west side of the entrance. Another small boat harbor lies outside the deep draft harbor to the south. This harbor includes two breakwater structures (Figure 2).

Objective

Because of Kawaihae Deep Draft Harbor's present and projected importance, the U.S. Army Engineer District, Honolulu (POH), at the request of the Harbors Division, Department of Transportation, State of Hawaii (HDOT), is developing and evaluating alternative plans for harbor deepening and modification of harbor structures to provide better protection from waves and surge (U.S. Army Engineer District, Honolulu 2006). The present study analyzes wave response of harbor alternatives in support of this planning.

Approach

The study described in this report was performed by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), in support of planning for Kawaihae Deep Draft Harbor. The approach consisted of the following components:

a. Develop incident wave climate summaries from available gauge data adjusted as needed to incorporate island sheltering effects at Kawaihae. The numerical wave model STWAVE provided estimates of island sheltering and refraction into Kawaihae Bay.

b. Use physical model and gauge data to calibrate and validate numerical wave model CGWAVE.

c. Use the numerical model CGWAVE to investigate alternative harbor modification plans.

Offshore wave data

Concurrently with this CHL study, POH installed field wave gauges outside the harbor entrance and at two locations inside the harbor. The outside gauges were capable of providing directional wave data. The inside gauges were single, nondirectional pressure sensors. Data from these gauges were a very valuable component of the present study, helping to establish characteristics of the incident wave climate and to determine wave transformation to harbor pier areas.

Wind wave and swell climate was investigated primarily with data from National Data Buoy Center (NDBC) buoy 51026, located offshore in deep water north of the island of Molokai, and NDBC buoy 51027, located southwest of the island of Lanai (Figure 1). One year of concurrent directional wave data are available from the two buoys and available evidence suggests that this year is typical of the wave climate. Wave data from the buoys were adjusted for additional island sheltering that would affect Kawaihae and for transformation in shallow water as the waves approach Kawaihae Deep Draft Harbor. The finite difference numerical wave transformation model STWAVE was used to help determine these adjustments. The wave climate study is presented in Chapter 2.

Numerical model for harbor waves

Numerical wave model CGWAVE, the present state-of-the-art CHL model for harbor wave response studies, was set up to cover the entire harbor and the area outside the harbor extending beyond the seaward limit of the entrance channel. The model was tested, calibrated, and validated, mainly using the field data recently collected at the harbor. Plans for modifying the harbor were developed by POH. As part of this study, the plans were refined based on initial screening runs with CGWAVE.

Study plans

A total of six harbor modification plans and the existing harbor were selected for detailed study. All plans include deepening the entrance channel to 13.7 m (45 ft) mean lower low water (mllw) and the harbor basin to 12.2 m (40 ft) mllw. Limited numerical model simulations of the existing harbor with existing depths (12.2 m (40 ft) in the entrance channel and 10.7 m (35 ft) in the harbor basin) and plan depths showed no significant difference in harbor response due to project depth in this range. Plans selected for study, with the exception of Plan 5, differ in the length and placement of stub breakwaters on the east side of the harbor entrance and extensions to the tip of the existing breakwater. Special features of each plan are:

a. Plan 1a. 229-m (750-ft) dogleg extension from the tip of the breakwater, oriented parallel to the entrance channel (Figure 4).

b. Plan 1b. same as Plan 1a but with dogleg extension length of 305-m (1000-ft) (Figure 4).

c. Plan 1c. same as Plan 1a but with dogleg extension length of 381-m (1250-ft) (Figure 4).

d. Plan 1d. same as Plan 1a but with dogleg extension length of 457-m (1500-ft) (Figure 4).

e. Plan 2a. 91-m (300-ft) stub extending from land opposite the breakwater tip, just north of the small boat basin entrance, oriented at approximately 230 deg azimuth (Figure 5).

f. Plan 2b. 85-m (280-ft) stub extending from land just north of the barge pier, south of the small boat basin entrance, oriented approximately perpendicular to the barge pier (Figure 6).

g. Plan 3. 128-m (420-ft) stub extending from land just west of the small boat basin entrance, replaces existing structure protecting the small boat basin, oriented approximately north/south (Figure 7).

h. Plan 4. 61-m (200-ft) straight extension from the tip of the breakwater and 61-m (200-ft) stub extending from land just west of the small boat basin entrance, replaces existing structure protecting the small boat basin, oriented approximately north/south (Figure 8).

i. Plan 5. 158-m (520-ft) gap opened in mid part of breakwater to create new harbor entrance, existing entrance closed with new breakwater segment, new entrance channel oriented southwest/northeast (Figure 9).

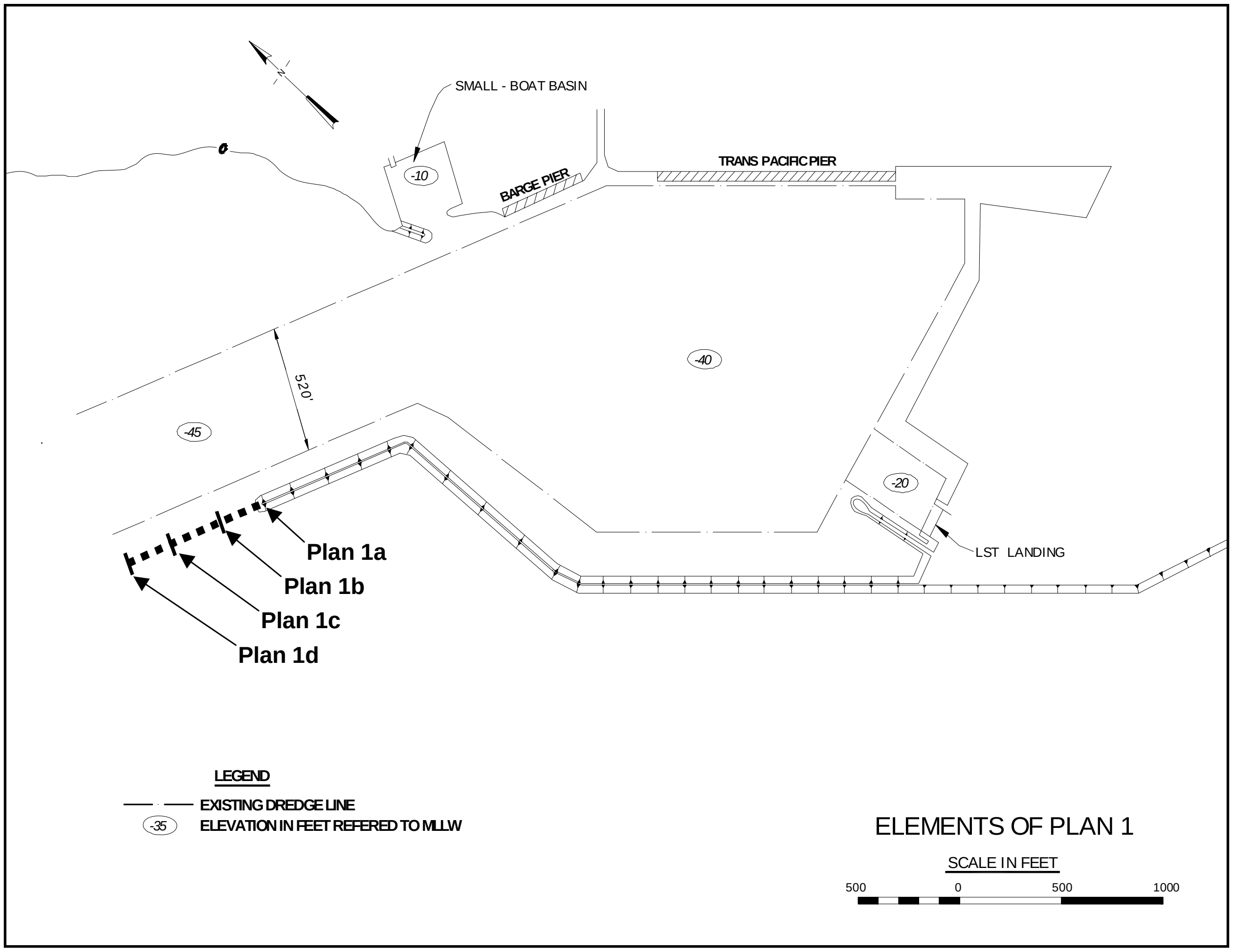

Figure 4. Kawaihae Deep Draft Harbor, Plans 1a, 1b, 1c, and 1d

Development and calibration/validation of the numerical model and test procedures is described in Chapter 3. Response of the alternative harbor plans to wind waves and swell (short waves) is presented in Chapter 4. Harbor oscillation characteristics (response to long waves) are presented in Chapter 5. The harbor response is related to wave climate and to relevant operational criteria at commercial piers.

Conclusions and recommendations are given in Chapter 6. This chapter is followed by references.

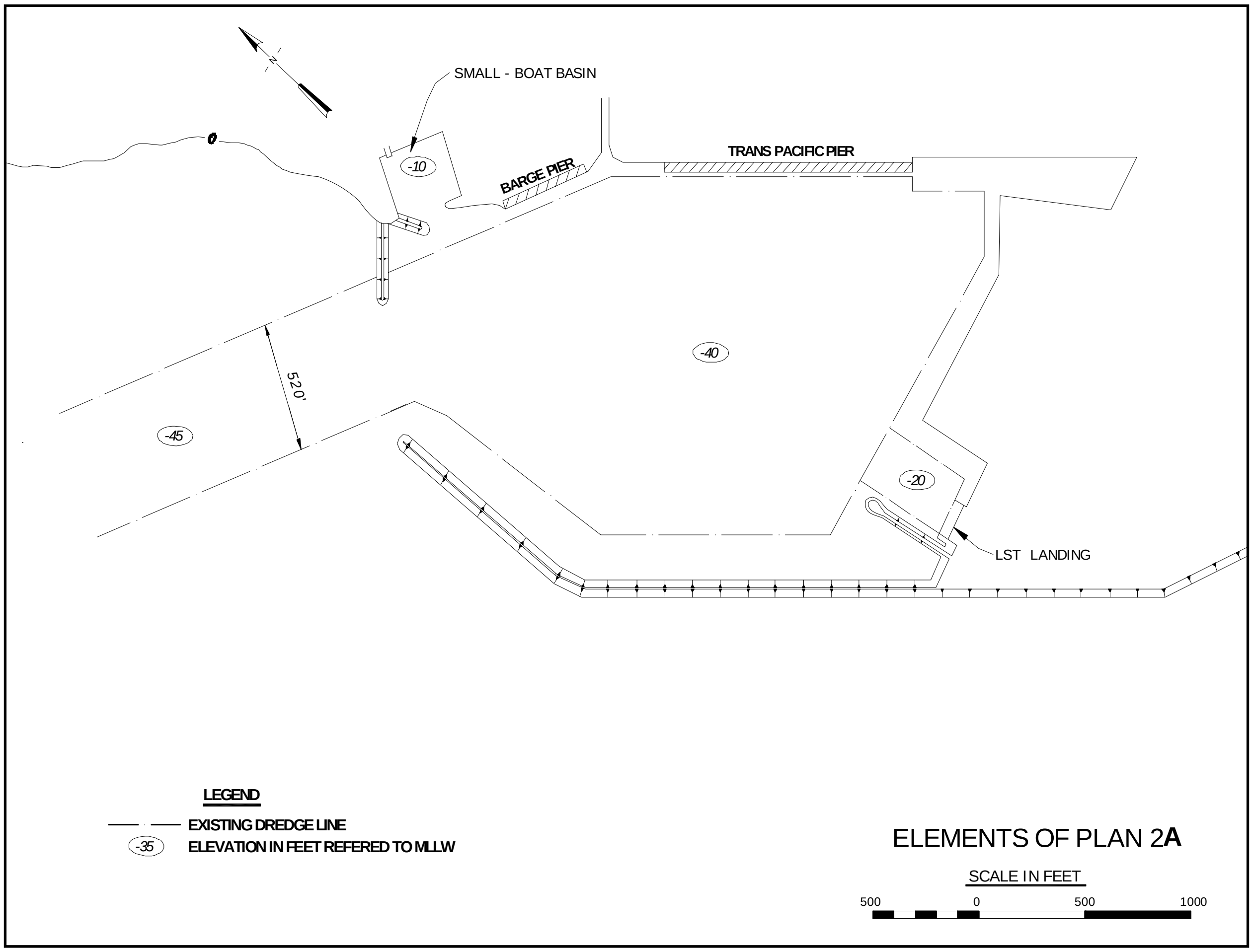

Figure 5. Kawaihae Deep Draft Harbor, Plan 2a

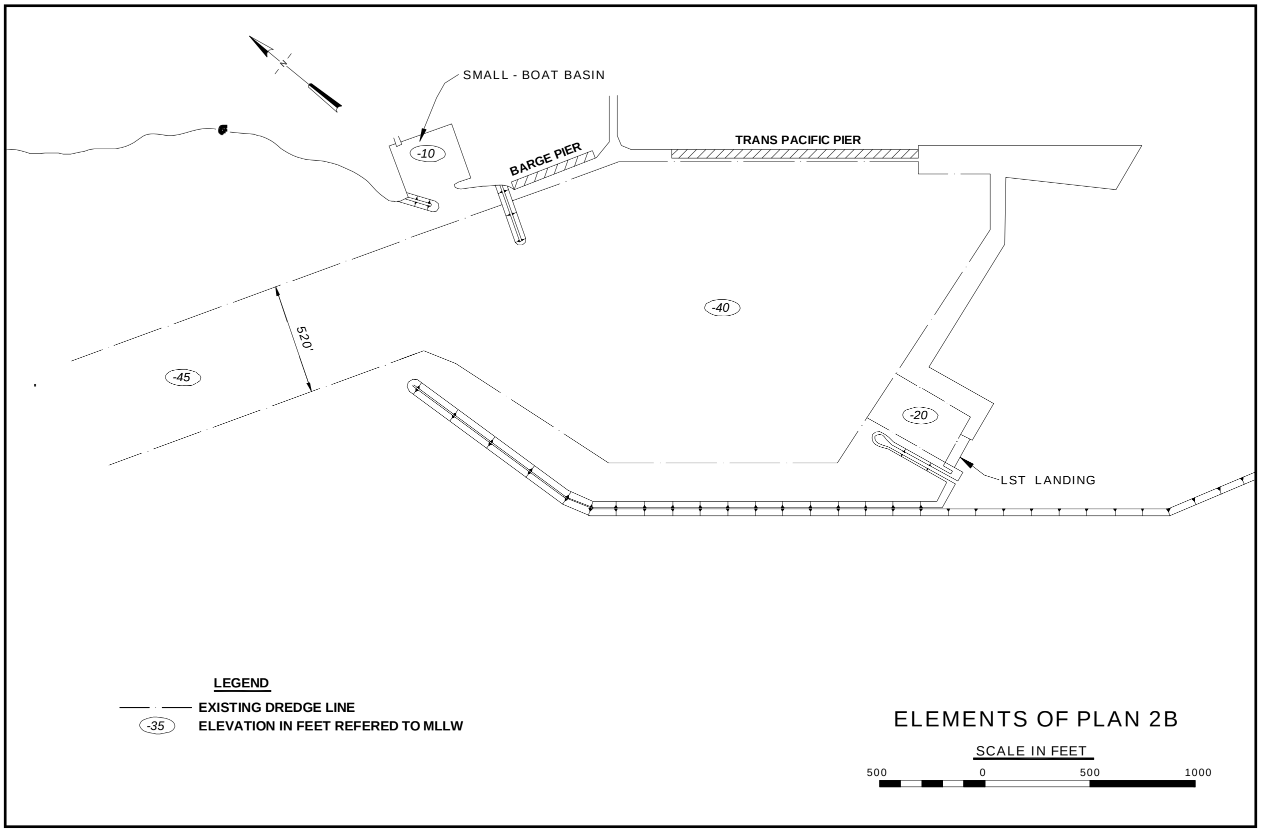

Figure 6. Kawaihae Deep Draft Harbor, Plan 2b

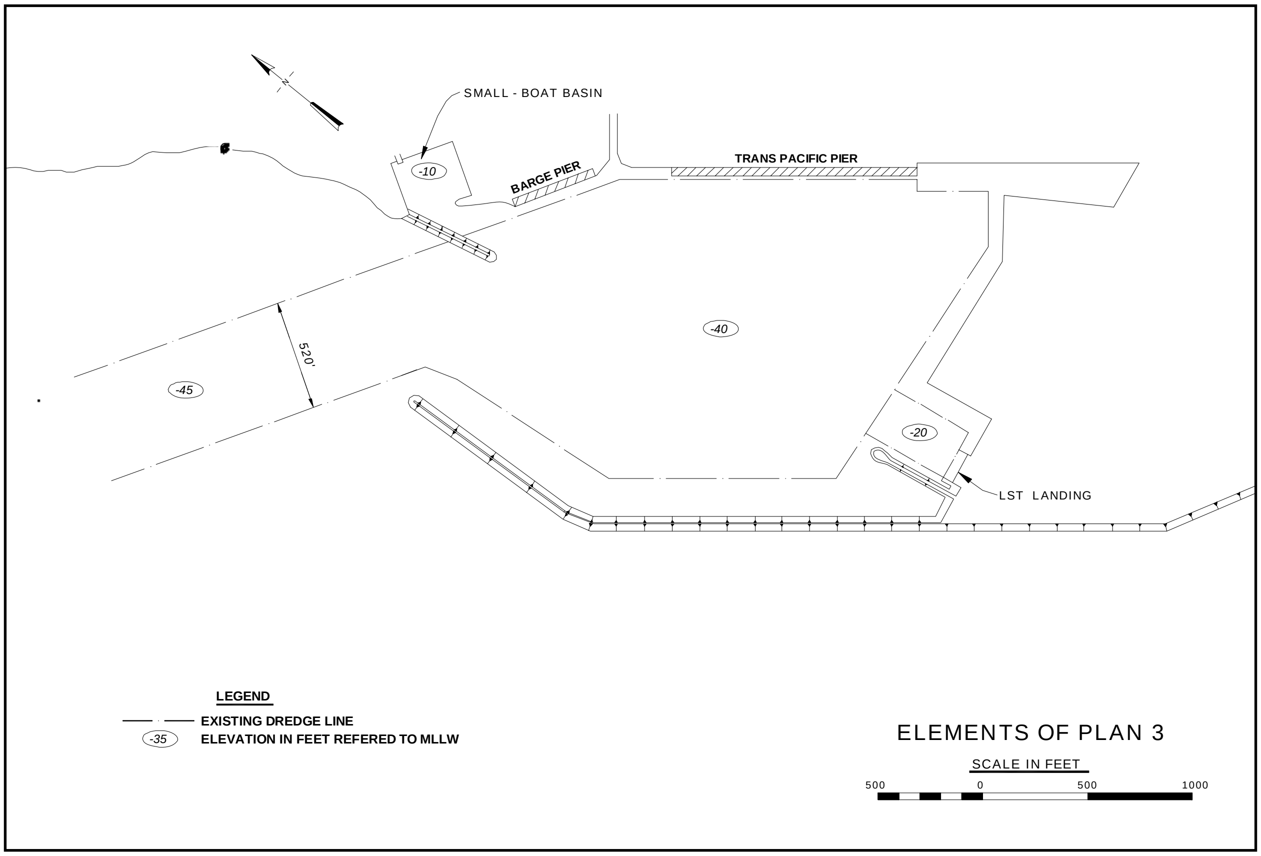

Figure 7. Kawaihae Deep Draft Harbor, Plan 3

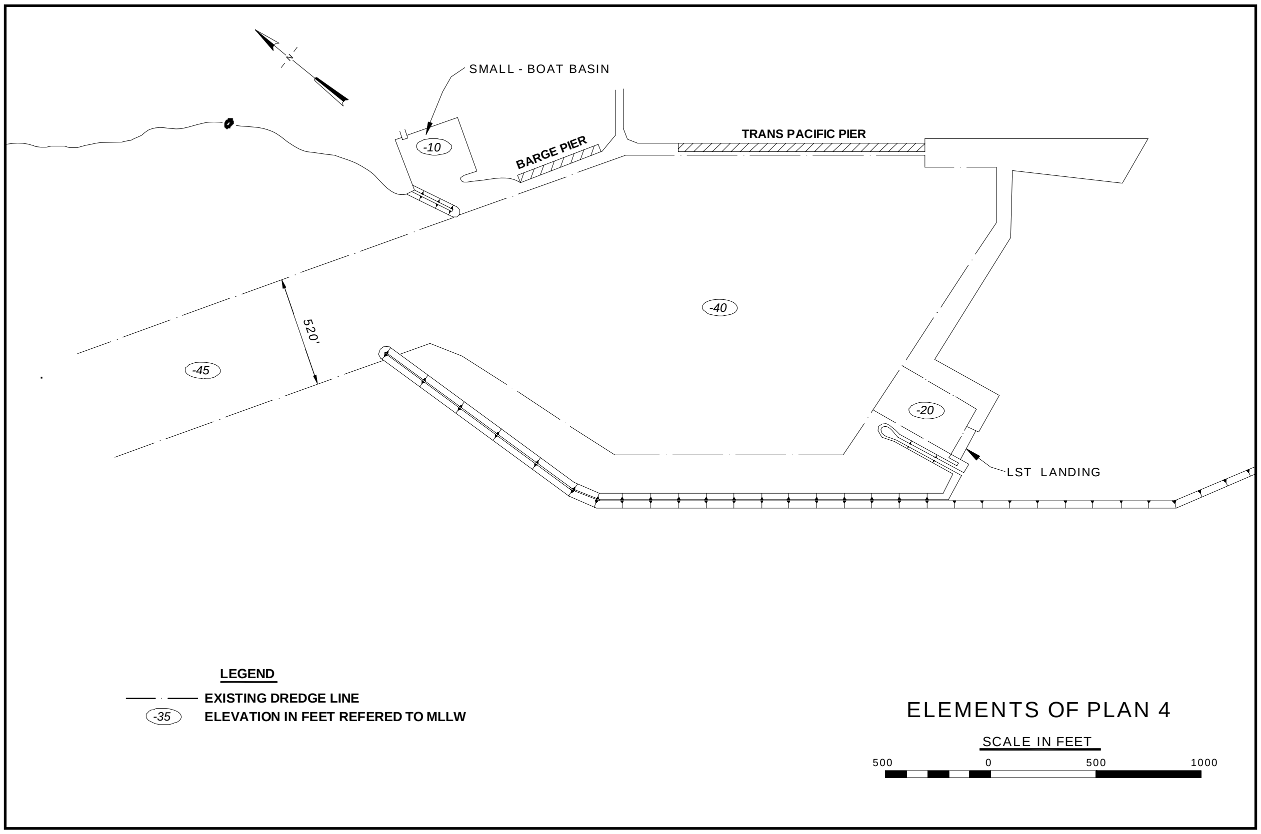

Figure 8. Kawaihae Deep Draft Harbor, Plan 4

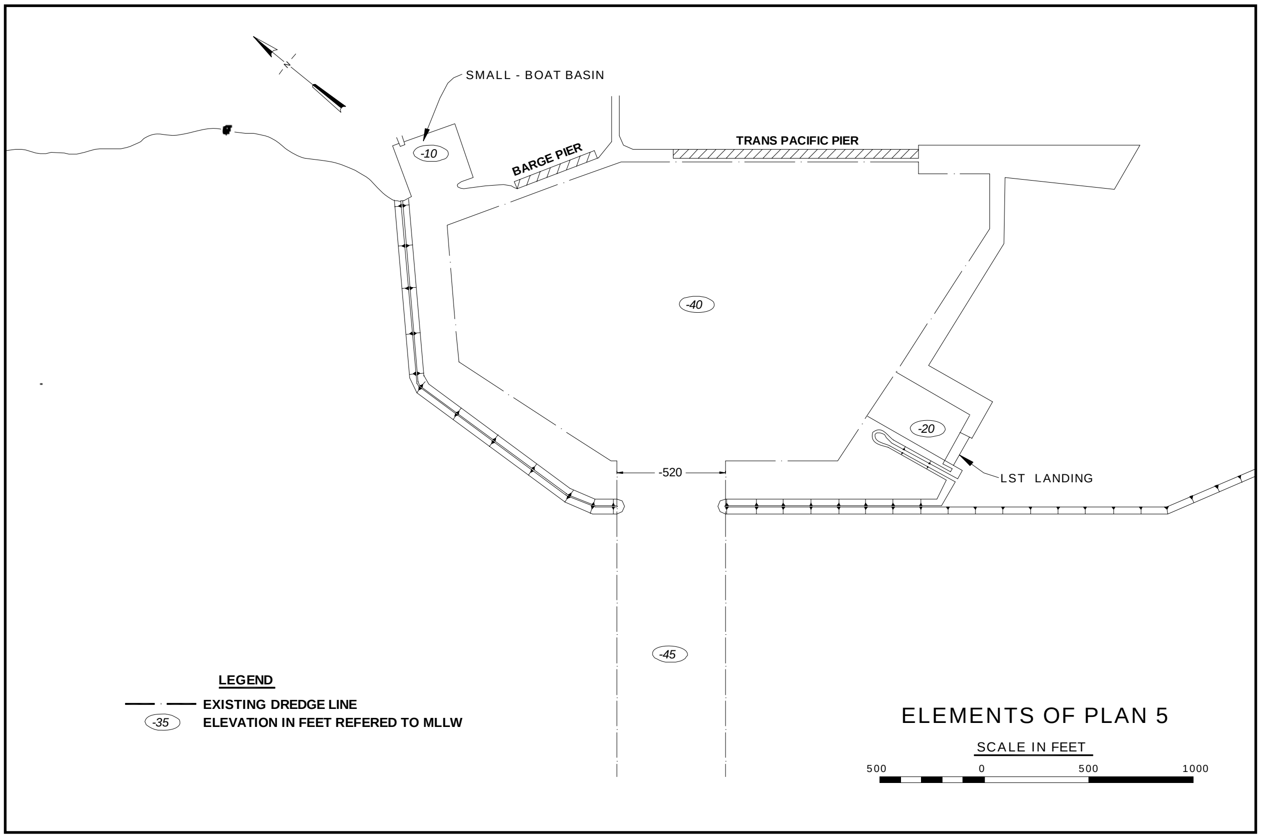

Figure 9. Kawaihae Deep Draft Harbor, Plan 5

2 Wind Wave and Swell Climate

Determination of wind wave and swell climate at Kawaihae Deep Draft Harbor requires a significant effort because no long-term measurements or hindcasts are available at this naturally sheltered site. The approach is to base wave climate on deep water directional data for waves incident to the Hawaiian Island chain and then use a numerical wave transformation model to incorporate island sheltering effects. Limited wave data at the harbor site provide a means of validating this approach.

Sources

When the wave climate part of this study was done, two sources of wind wave and swell field data were available to develop wave climate outside the harbor entrance (Table 1 and Figure 10). Both are deep water directional wave buoys operated by the National Data Buoy Center (NDBC) of the National Oceanic and Atmospheric Administration (NOAA). Deep water directional wave information is also available from the U.S. Army Corps of Engineers Wave Information Studies (WIS) hindcasting program. However, existing hindcasts at the time of study were produced two decades ago (Corson et al. 1986). They are of limited value in the Hawaiian Islands for two reasons. First, very little gauge data were available for calibration and validation. Second, limitations in meteorological data and computing capabilities resulted in a hindcast grid with only partial coverage of the Pacific Ocean basin, including grid-limited fetches to the west and southwest of the Hawaiian Islands. Since updated WIS hindcasts were not available at the time of this study, wind wave and swell climate was based solely on the NDBC directional buoy data. Subsequently, updated deep water WIS hindcasts have been completed for the years 1995-2004, but the in situ NDBC buoy measurements with good representation of study area exposures are still a primary source of wave climate data.

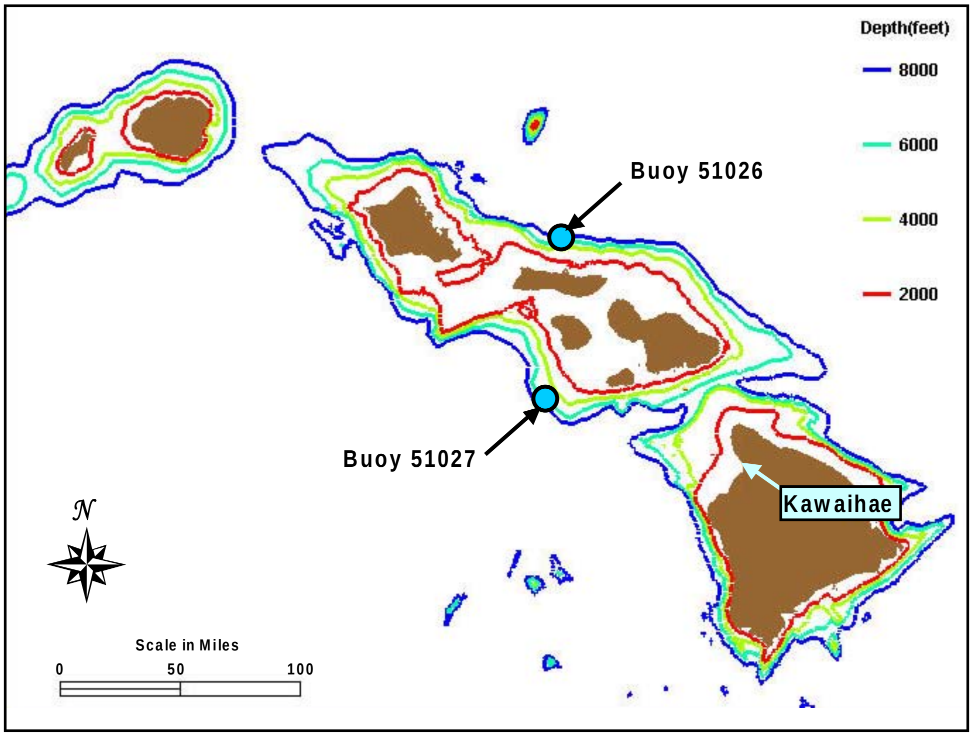

Figure 10. Location map for wave climate study

Another key source of wind wave and swell data for Kawaihae Harbor is a short-term deployment of wave gauges at the project site during 22 January to 23 March 2004 (Table 1). This field data collection was funded as part of the feasibility phase investigations and conducted by contract (Sea Engineering, Inc., and Nagamine Okawa Engineers, Inc. 2004). Two directional Acoustic Doppler Current Profiler (ADCP) gauges were placed in 17-m (56-ft) depth at the south side of the seaward end of the entrance channel. Additionally, two non-directional, bottom-mounted pressure gauges were placed inside the harbor in about 10-m (33-ft) depth near the north end of the barge pier and between the barge and Transpacific piers (Figure 11).

Table 1
Sources for Wave Climate Data

Source	Years	Latitude (deg N)	Longitude (deg W)
NDBC Buoy 51026 (N Molokai)	Jan 1993-Nov 1996	21.37	156.96
NDBC Buoy 51027 (SW Lanai)	Dec 1994-Nov 1995	20.4	157.1
POH Gauges 0388 & 1113 (outside Kawaihae Harbor)	Jan-Mar 2004	20.04038	155.83967
POH Gauge 10598 (inside Kawaihae Harbor, N of barge pier)	Jan-Mar 2004	20.03803	155.83967
POH Gauge 10212 (inside Kawaihae Harbor, between barge & Transpacific piers)	Jan-Mar 2004	20.03688	155.82957

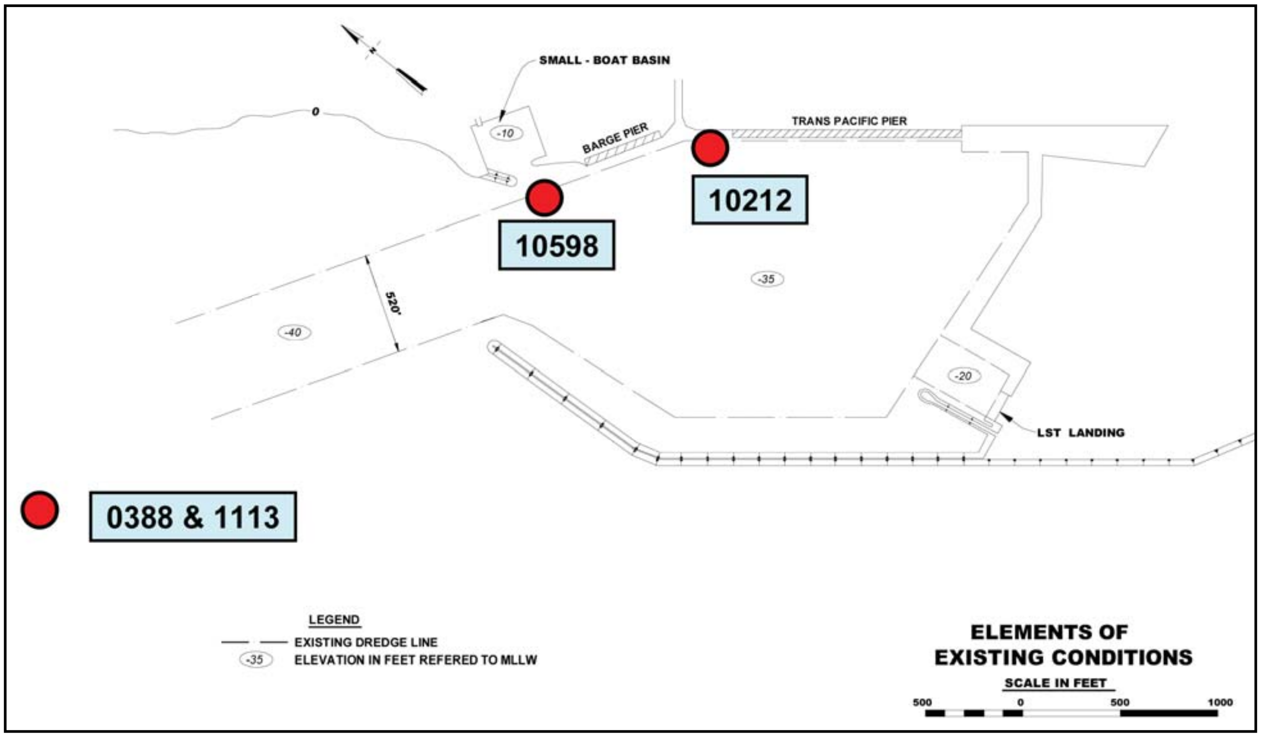

Figure 11. Location map for Kawaihae Deep Draft Harbor gauges

Deepwater Wave Climate

The directional buoy north of Molokai (NDBC buoy 51026) collected data from January 1993 through November 1996, except for a gap in May-September 1994. The directional buoy southwest of Lanai (NDBC buoy 51027) operated from December 1994 through November 1995. Since buoy 51026 was operational for the same 12-month period, the two buoys provide an estimate of annual wave climate impacting the Hawaiian Islands from the south clockwise through northeast. Those exposure directions include all directions of importance to Kawaihae Harbor.

NDBC buoy 51026 provides four reasonably complete years of directional wave data. The four annual wave climate estimates were intercompared in an earlier study (Thompson and Demirbilek 2002). No major differences in winter, summer, or annual wave climate were noted among the four years. Thus, the available directional data suggest that the 12-month period covered by both NDBC buoys provides a representative wave climate estimate. Further confirmation was obtained by comparing the year 1995 to the 10 years 1995-2004 at a station near the buoy 51027 location in the recently completed WIS hindcasts. The two WIS climate summaries are very similar to each other for all important exposure directions. Although Jan-Dec 1995 is shifted by one month from the wave climate year in the present study (Dec 94-Nov 95), the evidence strongly suggests that the year of concurrent buoy measurements is representative of the wave climate incident to Kawaihae.

The NDBC buoy 51026 is exposed to a wide range of incident wave directions. The buoy has a wide-open exposure to directions from northwest clockwise to southeast. The buoy is somewhat sheltered from waves approaching the Hawaiian Islands from the west, principally by the Island of Oahu.

A wave rose for buoy 51026 for the selected year shows a predominance of waves from the northwest and east (Figure 12). The width of the radial bars indicates significant wave height, H_S, band. The lowest wave height bands are shown nearest the center of the rose. The radial bars become narrower toward the outer end of each bar, indicating increasing wave heights. Bar width begins increasing again for the highest wave height bands (H_S greater than 5.5 m (18 ft)), but H_S values in this range are rare, as indicated by a few very short, wider sections at the outer end of some bars. A rose of peak wave period, T_p , for the same time period is shown in Figure 13.

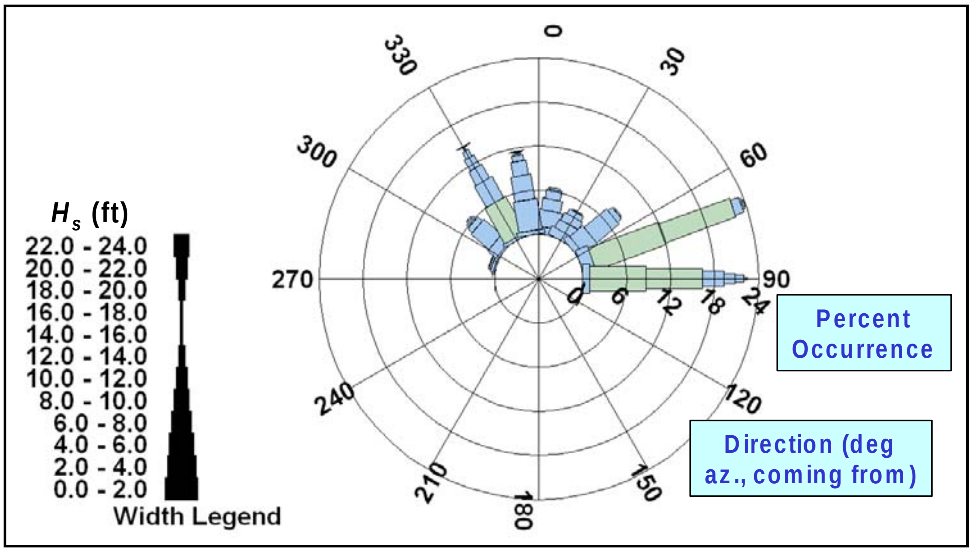

Figure 12. Wave height rose, Dec 94-Nov 95, NDBC buoy 51026

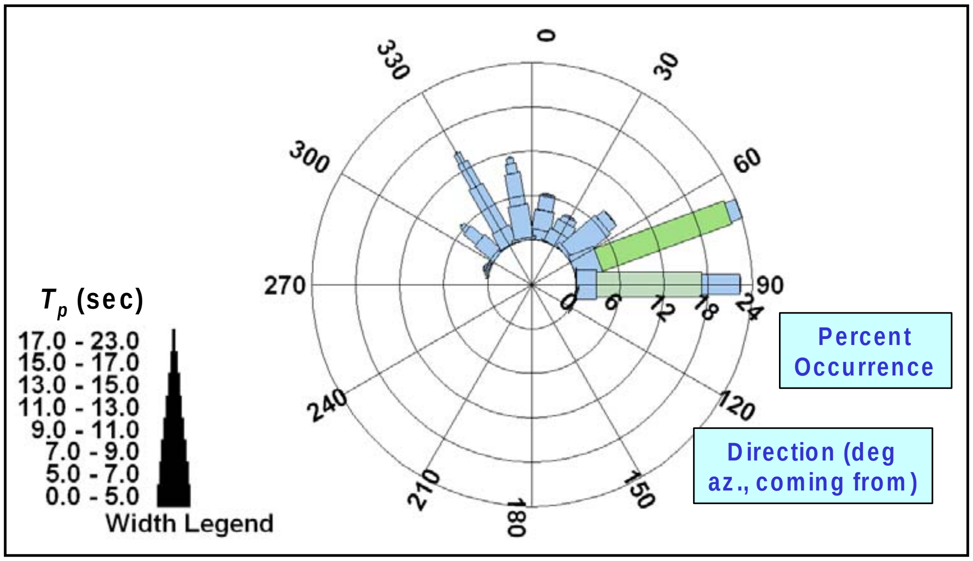

Figure 13. Wave period rose, Dec 94-Nov 95, NDBC buoy 51026

The NDBC buoy 51027 also has a wide range of exposure, but it is quite different from that of buoy 51026. Buoy 51027 is open from southeast clockwise to west northwest. It is highly sheltered from northerly and easterly directions by the various islands in the Hawaiian Island chain. The wave rose for buoy 51027 shows predominance of waves from east southeast, south, and west northwest (Figure 14). The corresponding T_p rose is shown in Figure 15.

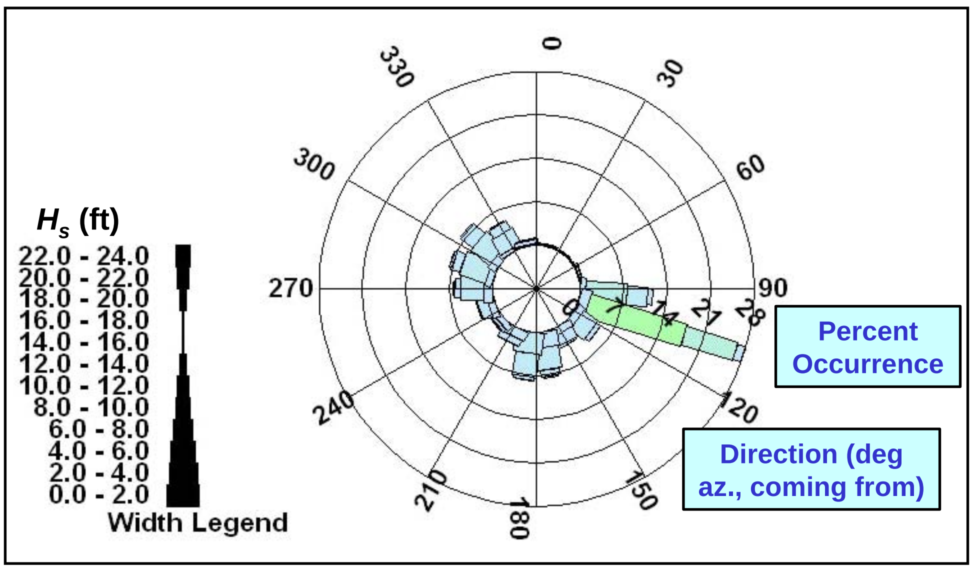

Figure 14. Wave height rose, Dec 94-Nov 95, NDBC buoy 51027

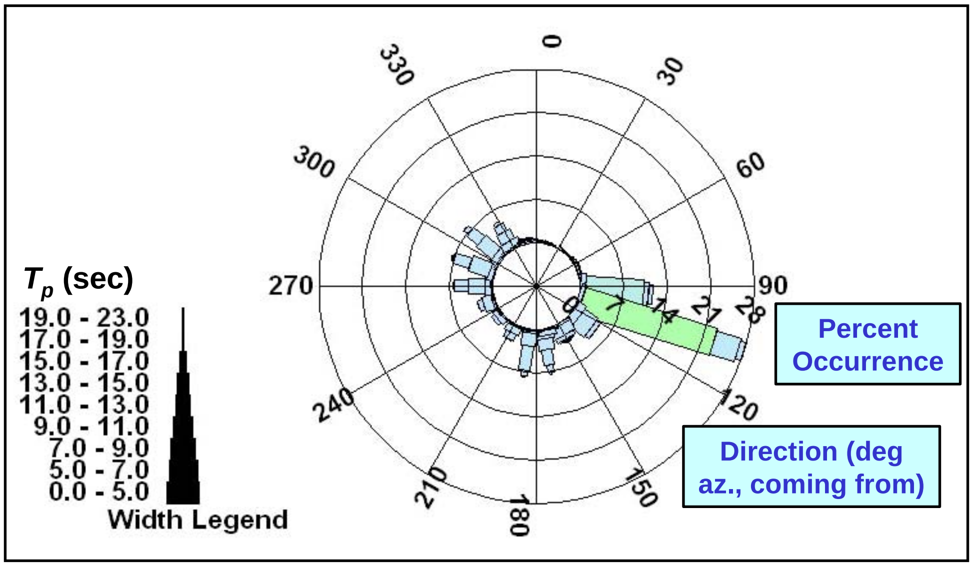

Figure 15. Wave period rose, Dec 94-Nov 95, NDBC buoy 51027

The open exposures of buoys 51026 and 51027 together give a fairly complete representation of the wave climate approaching Kawaihae Harbor. However, that wave climate from some directions will be highly modified by island sheltering before arriving at Kawaihae. A numerical modeling effort to estimate island sheltering effects and determine wave climate at Kawaihae is discussed in the following section.

Wave Transformation to Study Site

Transformation around Hawaiian Islands to Kawaihae Bay

The numerical model used for transformation around the Hawaiian Islands, STWAVE (**ST**eady-state spectral **WAVE** model), is the standard CHL tool for studies of wave transformation over broad areas of complex, shallow nearshore bathymetry. STWAVE is a steady state finite difference model used in the calculation of wave growth and transformation (Smith, Sherlock, and Resio 2001). Typically, the model area covers a rectangular domain with maximum dimension of about 48 km (30 miles) or less, including regions with complex, shallow water depths. Typical model resolution is 200 m (600 ft) or less. The present model application is atypical in that it is designed to estimate large-scale sheltering effects. It covers an unusually large area and employs a very coarse grid.

The STWAVE model is interfaced with commercially available Corps of Engineers-supported software to assist in preparing model grids and other inputs and in displaying model results. This software-assisted pre- and post-processing is needed in any practical application. More information on STWAVE is available from the CHL internet web site. The software package for pre- and post-processing is part of the Surface Water Modeling System (SMS). The SMS software is also described through the model web site.

Three rectangular-shaped finite difference grids for STWAVE were constructed using SMS (Figure 16). These island-scale grids were built in State Plane coordinate zone Hawaii 2 – 5102 to best represent sheltering by Maui, Molokai, Lanai, and Kahoolawe. Grid resolution is 1 km (0.6 mile). Parameters for creating the grids in SMS are given in Table 2. The angle of rotation is expressed as the direction, in Cartesian coordinates, toward which a wave approaching perpendicular to the offshore boundary is going, following SMS input requirements. Multiple grids were needed to model the full range of partially-blocked incident directions that may affect Kawaihae because of the model limitation discussed in the following paragraph. Model boundaries were extended seaward far enough to encompass all Hawaiian Islands relevant to the exposure at Kawaihae. Bathymetric data for the Hawaiian Islands were obtained in digital form from the NOAA National Geophysical Data Center GEODAS database.

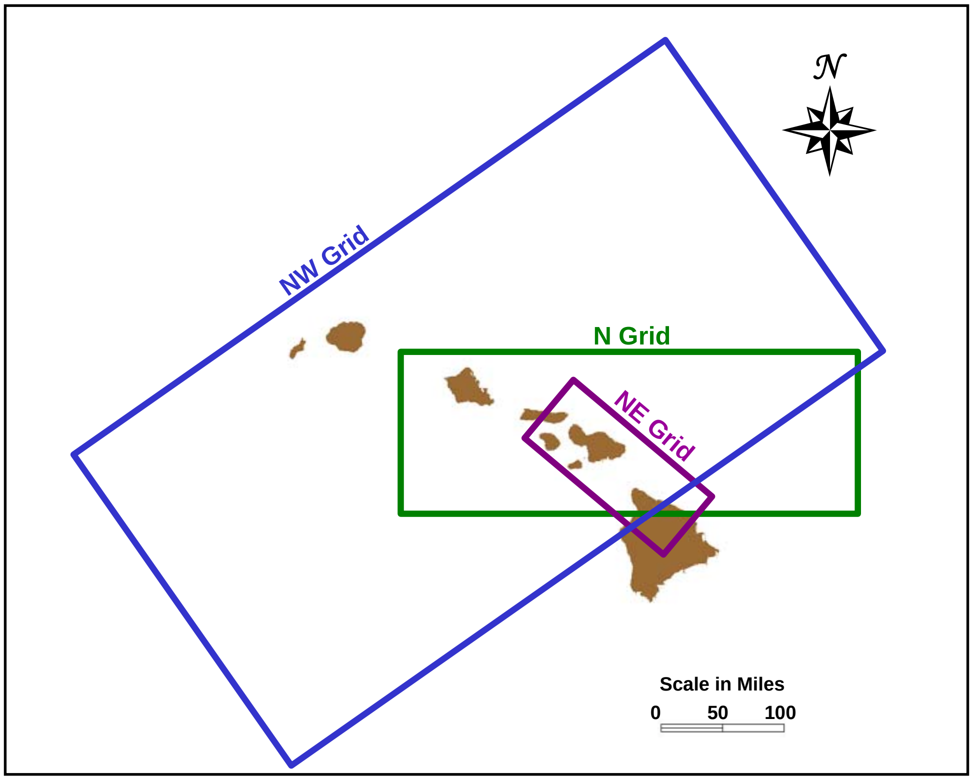

Figure 16. STWAVE grid coverage areas for transformation around Hawaiian Islands

Table 2
Specifications for STWAVE Island-Scale and Local Transformation Grids in SMS

Parameter	NW Grid	N Grid	NE Grid	Local Grid
Origin x, State Plane, m	-200,000	240,000	511,500	462,120
Origin y, State Plane, m	57,000	200,000	135,200	127,880
Angle of rotation, deg	305	270	230	0
Cell dimension x, m	1000	1000	1000	20
Cell dimension y, m	1000	1000	1000	20
Grid dimension x, m	550,000	240,000	100,000	3,000
Grid dimension y, m	1,000,000	650,000	280,000	9,460
Number of columns	550	240	100	150
Number of rows	1000	650	280	473

The STWAVE model has a limitation in modeling waves coming from directions that are highly oblique to the grid orientation. When incident wave direction is more than about 45-50° away from perpendicular to the offshore grid boundary, model limitations can create artificial decreases in wave height as waves propagate into the grid. These model effects also appear if waves refract to highly oblique angles within the grid. Thus, model grid orientation was selected to minimize the occurrence of highly oblique wave angles in regions of interest.

A unit significant wave height and a representative range of peak wave periods and peak wave directions were modeled, based on the buoy wave climate (Table 3). Every combination of the three wave parameters was modeled in STWAVE, giving a total of 91 wave conditions. Directions were chosen to cover the partially sheltered exposure of the harbor entrance to the west, northwest, and north.

Table 3
Incident Wave Parameters and Corresponding STWAVE Island-Scale Grids

Grid	Incident H_s m	Incident T_p sec	Incident θ_p (deg azimuth, coming from)
NW	1	8, 10, 12, 14, 16, 18, 20	295, 305, 315, 325, 335
N	1	8, 10, 12, 14, 16, 18, 20	345, 355, 5
N	1	8, 10, 12, 14, 16	15, 25, 35, 45
NE	1	6, 8, 10, 12, 14	55, 65, 75

For each STWAVE input height/period/direction combination, SMS was used to generate a directional wave spectrum in deep water. Spectral frequencies ranged from 0.04 Hz to 0.34 Hz in 0.01-Hz intervals. Spectral direction components covered ±85° from normal incidence to the grid, in 5° increments.

Water levels at Kawaihae vary over a relatively small range. The tidal datum is mean lower low water (mllw). Mean tide level is 0.2 m (0.8 ft) above mllw. Mean higher high water is 0.6 m (2.0 ft) above mllw. Since water level variations are small, only one water level, mllw, was used for STWAVE modeling.

Wave sheltering patterns for two important exposure directions are illustrated in Figures 17 and 18. Peak wave direction is represented with θ_p. For θ_p = 295° azimuth, H_s at Kawaihae is about 30 percent less than the incident H_s due to island sheltering. The vectors indicate wave direction south of Lanai around buoy 51027 has turned to more of an approach from the west at Kawaihae. Also, H_s around buoy 51027 is reduced due to island sheltering. For this incident direction, buoy 51027 is preferable to buoy 51026 for best representing waves at Kawaihae. For θ_p = 335° azimuth, H_s at Kawaihae is much less than the incident H_s due to island sheltering, primarily from Molokai, Lanai, and Maui and from the northern tip of Hawaii. The vectors indicate significant turning of wave direction, with waves coming more from west on the lee side of the islands. Buoy 51027 is more exposed than Kawaihae and the H_s around buoy 51027 is significantly higher than at Kawaihae. For this incident direction, buoy 51026, with proper reduction for sheltering, may be preferable to buoy 51027 for best representing waves at Kawaihae.

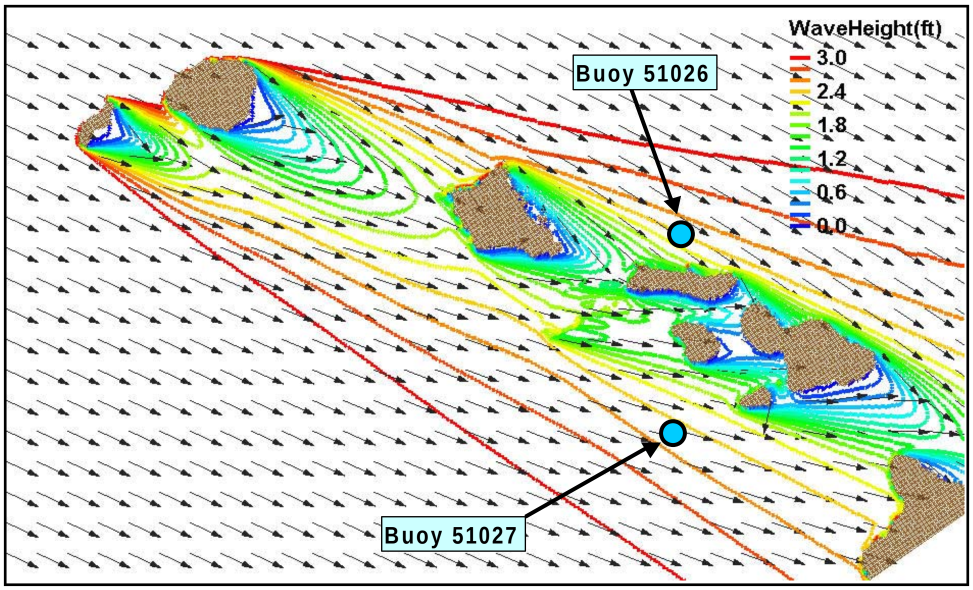

Figure 17. Wave transformation pattern, NW grid, Hs = 1 m (3.3 ft), Tp = 14 sec, θp = 295° azimuth

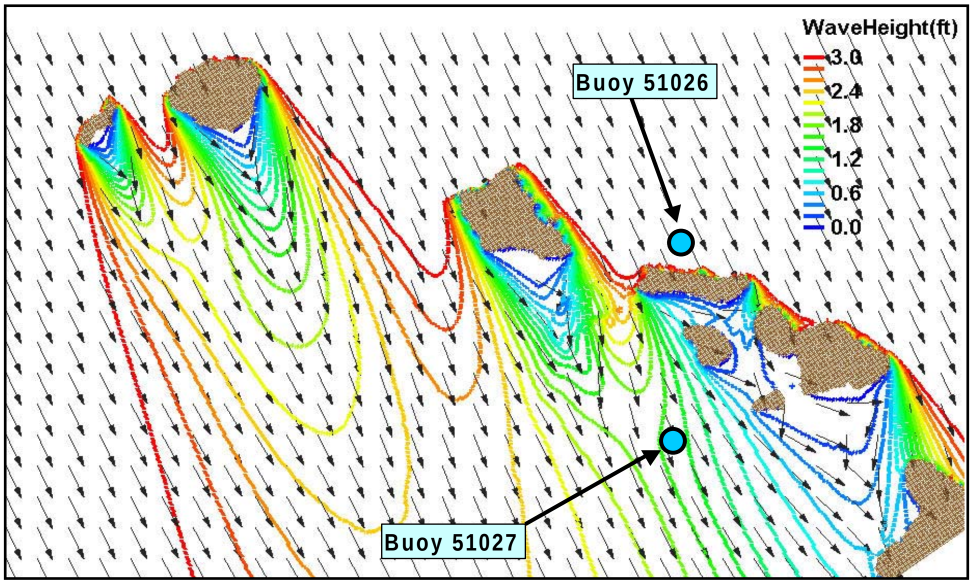

Figure 18. Wave transformation pattern, NW grid, H_s = 1 m (3.3 ft), T_p = 14 sec, θ_p = 335 deg azimuth

Six special output stations were designated in each grid offshore from Kawaihae Deep Draft Harbor. A station west of the harbor in about 130-m (426-ft) depth was selected to represent wave climate in Kawaihae Bay and to interface with the seaward boundary of a local STWAVE grid. The island-scale STWAVE output was further processed to compute transformation table ratios relating incident wave conditions to the selected output station.

Using these STWAVE results, the 1-yr time history of waves at buoys 51026 and 51027 was transformed to 130-m (426-ft) depth in Kawaihae Bay. The procedure, developed by a combination of experimentation and judgment, involved: 1) determining if a usable buoy observation was available at each observation time, 2) applying sheltering as needed to transform H_s and θ_p, and 3) combining observations from both buoys if both had usable observations. A factor F_{STWAVE} was calculated as needed for each buoy observation to apply the sheltering in step 2. The factor is the ratio of H_s at Kawaihae Bay to H_s at the buoy location, calculated by interpolation from the STWAVE runs that best matched the observed T_p and bracketed the observed θ_p. Wave direction transformation was calculated similarly, but with actual wave direction values rather than ratios.

Data from buoy 51026 were treated as follows, based on the direction arcs shown in Figure 19:

- buoy 51026 direction of 290-300° azimuth: apply STWAVE sheltering, including factor F_{STWAVE} to transform H_s; use only if $(H_s)_{51027}$ is not usable or if F_{STWAVE} x $(H_s)_{51026} > (H_s)_{51027}$

- buoy 51026 direction of 300° clockwise to 50° azimuth: apply STWAVE sheltering; use in all cases

- buoy 51026 direction of 50° clockwise to 290° azimuth: assume calm (set H_s, T_p, and θ_p equal to zero); Kawaihae is not exposed to these directions and/or buoy 51026 has partially sheltered exposure

Data from buoy 51027 were treated as follows, based on the direction arcs shown in Figure 20:

- buoy 51027 direction of 180-215° azimuth: apply sheltering due to west part of Island of Hawaii; reduce H_s based on portion of the directional spectrum blocked by Keahole Point and set θ_p = 215° azimuth

- buoy 51027 direction of 215-270° azimuth: assume no sheltering and use in all cases (i.e., F_{STWAVE} = 1 and θ_p unchanged)

- buoy 51027 direction of 270-300° azimuth: assume no sheltering; use unless buoy 51026 seems to have captured the same wavetrain more effectively, defined as $F_{STWAVE} \times (H_s)_{51026} > (H_s)_{51027}$ and difference between T_p values less than 4 sec

- buoy 51027 direction of 300-330° azimuth: apply STWAVE sheltering; use only if no usable observation from buoy 51026

- buoy 51027 direction of 330-180° azimuth: assume calm (set H_s, T_p, and θ_p equal to zero); Kawaihae is not exposed to these directions and/or buoy 51027 has partially sheltered exposure

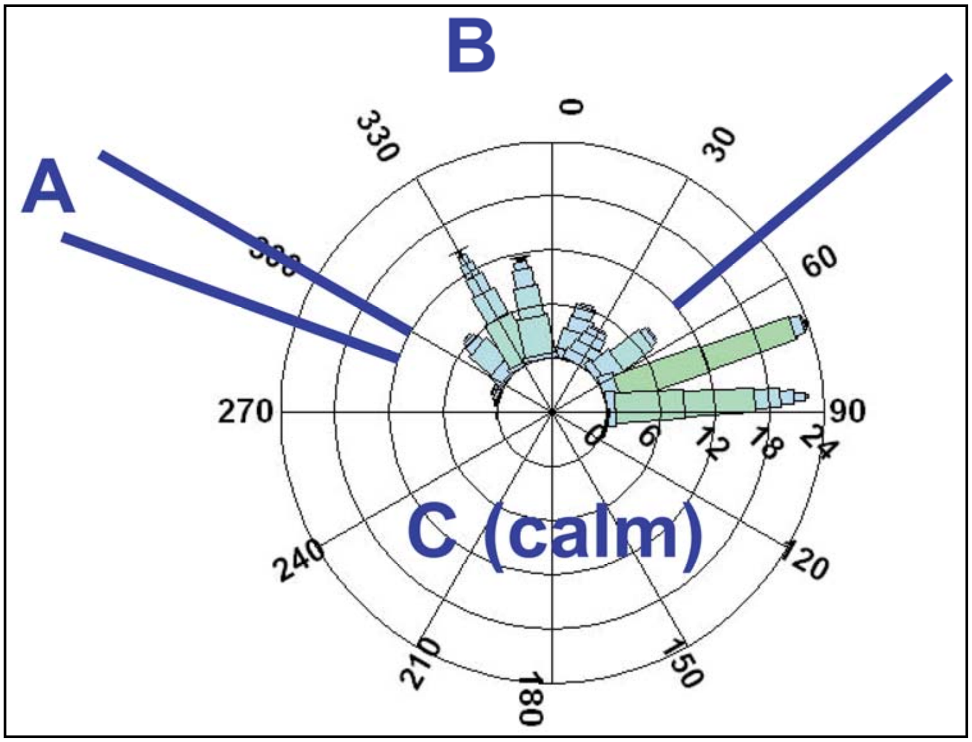

Figure 19. Procedure for transferring measured wave climate to Kawaihae Bay, NDBC buoy 51026

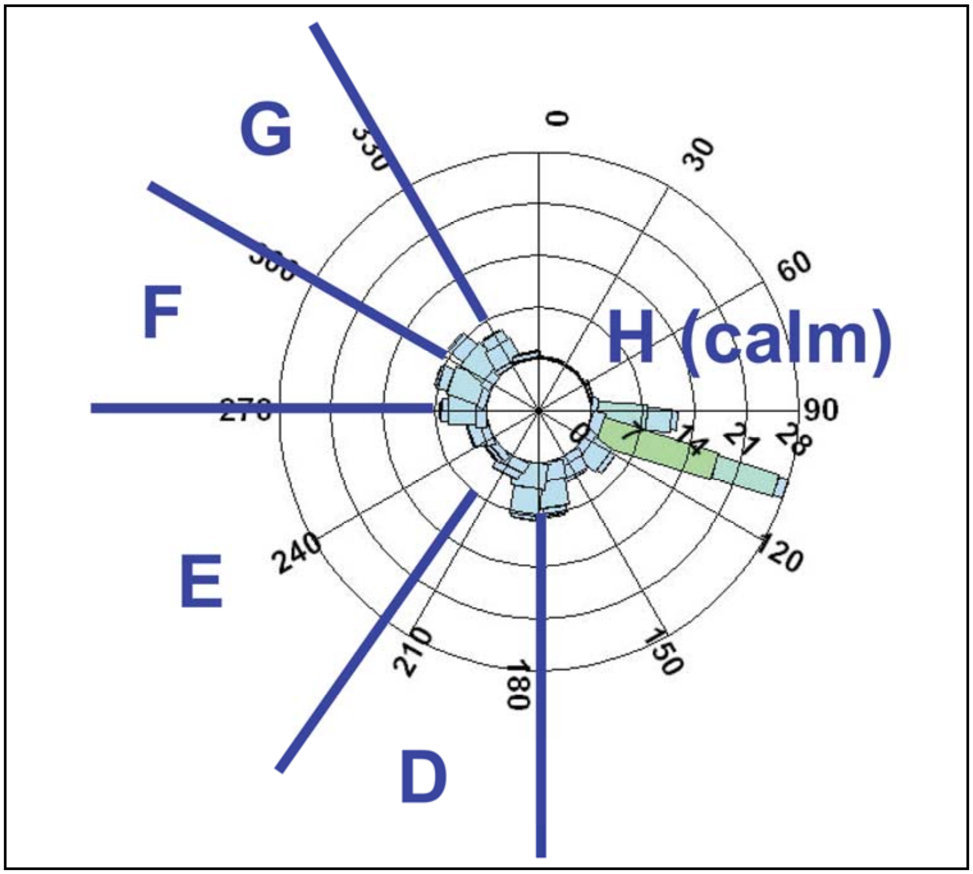

Figure 20. Procedure for transferring measured wave climate to Kawaihae Bay, NDBC buoy 51027

When both buoys had accepted observations at the same time, it was assumed that two different wave trains were present and that energy from both would appear at Kawaihae. To represent the combined energy, significant wave height was computed as the square root of $[F_{STWAVE} \times (H_s)_{51026}]^2 + [F_{STWAVE} \times (H_s)_{51027}]^2$. Values of T_p and θ_p at Kawaihae were based on the buoy with the higher transformed significant height.

The above guidelines were applied to the 1-yr buoy time histories of incident waves to calculate a 1-yr wave time history at the selected Kawaihae Bay station. Although a multi-year time history of data would be preferred if available, the 1-yr time history can be expected to provide a good estimate of the statistical information needed for comparing harbor plans. The main basis for comparing plans is the H_s exceeded 10 percent of the time, which is determined by fairly common high wave events in the climate and not much affected by extreme storms that may occur in some years. Multiple years of data from buoy 51026 and from recent WIS hindcasts at a point near buoy 51027 support the use of the selected year as typical of the wave climate.

Wave climate at the Kawaihae Bay station is summarized in Figures 21-23. The percentage of calms is 46.2 percent. The H_s rose shows a concentration of waves coming from the west northwest and southwest (Figure 21). A presence of high wave events is evident from all directions between 215° and 310° azimuth. Low wave conditions from sheltered directions to the northwest (310-350°) are also fairly common. Figure 22 shows that the highest H_s are 3.4-3.7 m (11-12 ft), coming from 270-290° azimuth. Waves from south of west can reach H_s of up to 2.4 m (8 ft). Waves from the northwest (310-350°) have H_s below 0.3 m (1 ft) in nearly all cases. Figure 23 shows the percent occurrence of T_p versus θ_p. The range of T_p values is reasonably consistent from about 7-19 sec for most direction bands.

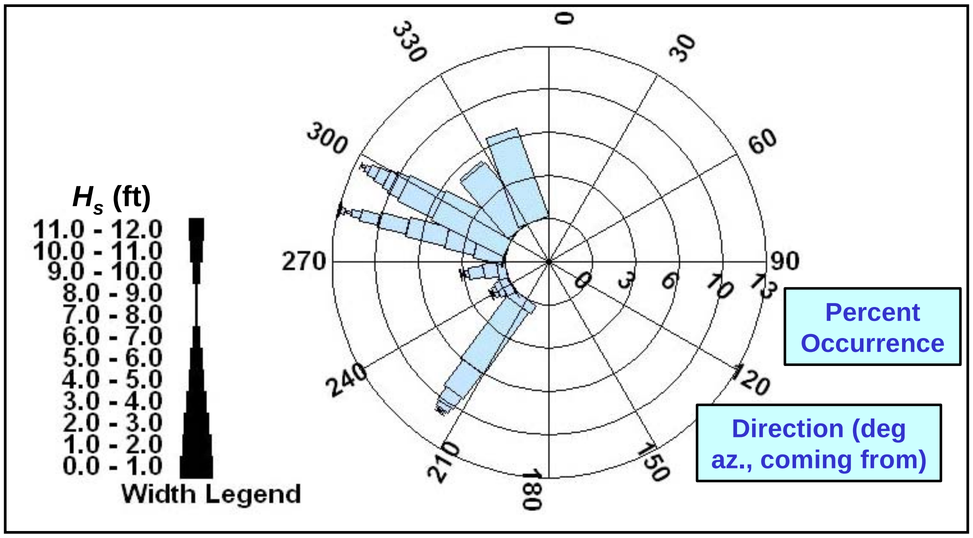

Figure 21. Wave height rose, Dec 94-Nov 95, Kawaihae Bay, 130-m (426-ft) depth

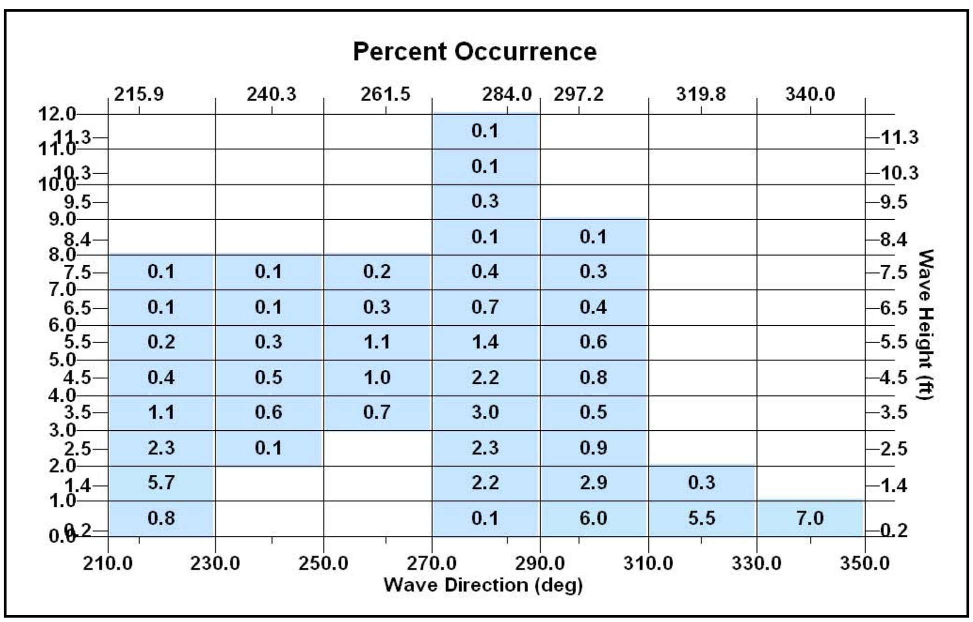

Figure 22. Percent occurrence, H_s vs. θ_p, Dec 94-Nov 95, Kawaihae Bay, 130-m (426-ft) depth

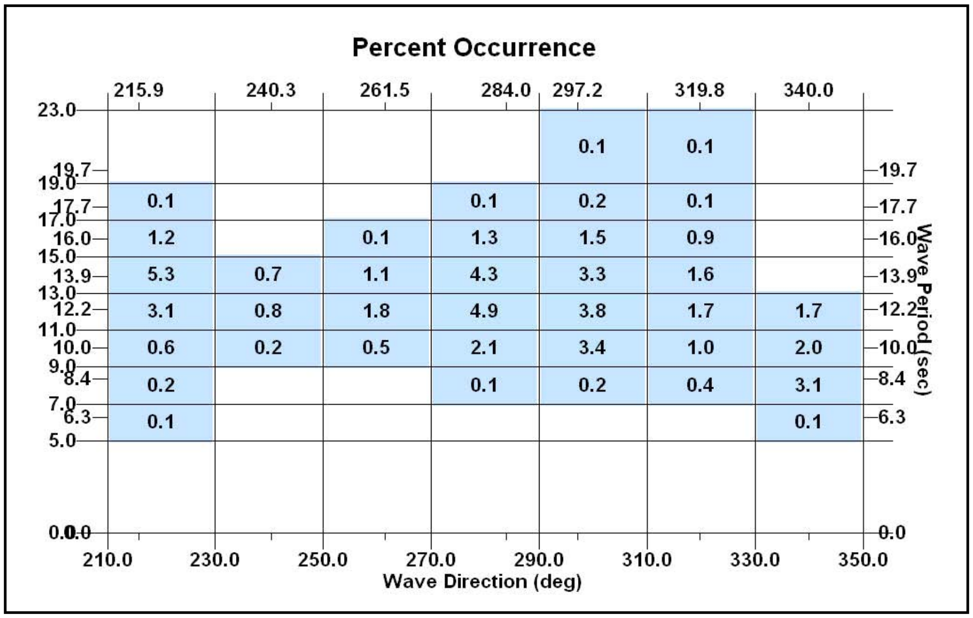

Figure 23. Percent occurrence, T_p vs. θ_p, Dec 94-Nov 95, Kawaihae Bay, 130-m (426-ft) depth

Local transformation in Kawaihae Bay

The Kawaihae Bay wave climate is in relatively deep water. For two reasons, wave climate is needed at shallower depths, closer to the harbor. First, it is helpful to take advantage of field data collected at the entrance to Kawaihae Deep Draft Harbor to validate the wave climate developed from distant buoys. Second, the seaward boundary of the harbor wave model CGWAVE is located closer to the harbor. A local STWAVE grid was created to model wave transformation between 130-m depth and the harbor (Figure 24). This local grid was built in State Plane coordinate zone Hawaii 1 – 5101. Grid resolution is 20 m (66 ft). Parameters for creating the grid in SMS are given in Table 2. The seaward model boundary extends to the 130-m (427-ft) depth Kawaihae Bay station. The GEODAS bathymetric database was supplemented with detailed nearshore data collected with the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) surveying system (Figure 25). The SHOALS surveys were funded by the Honolulu District.

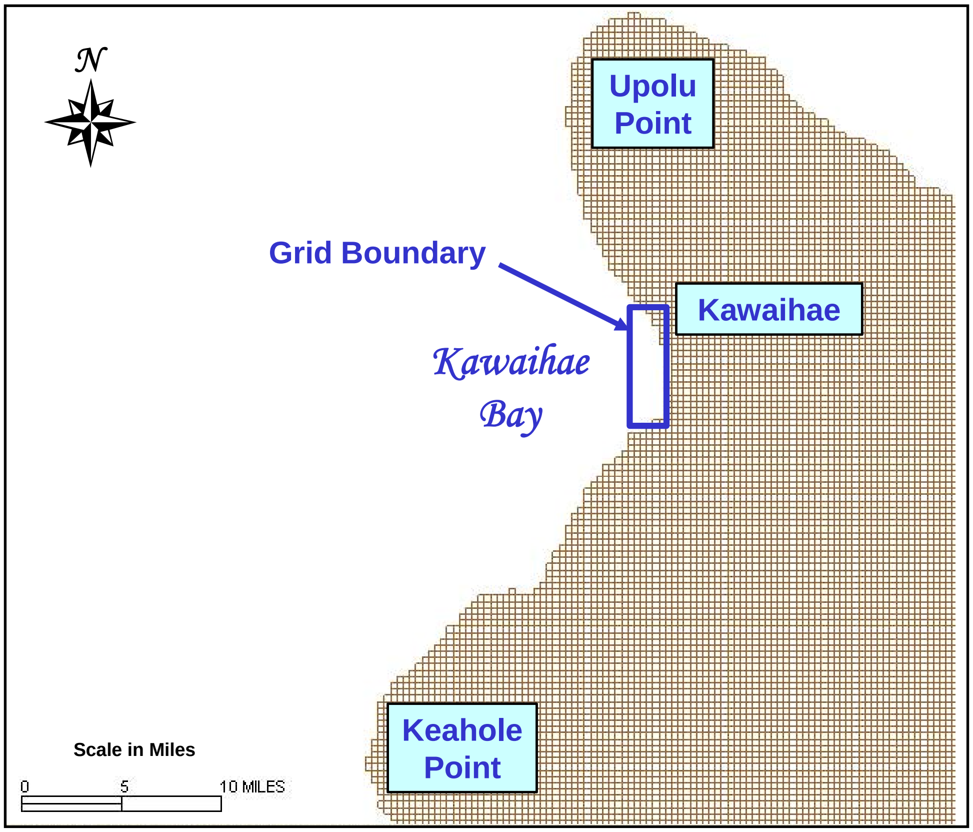

Figure 24. STWAVE local grid coverage area

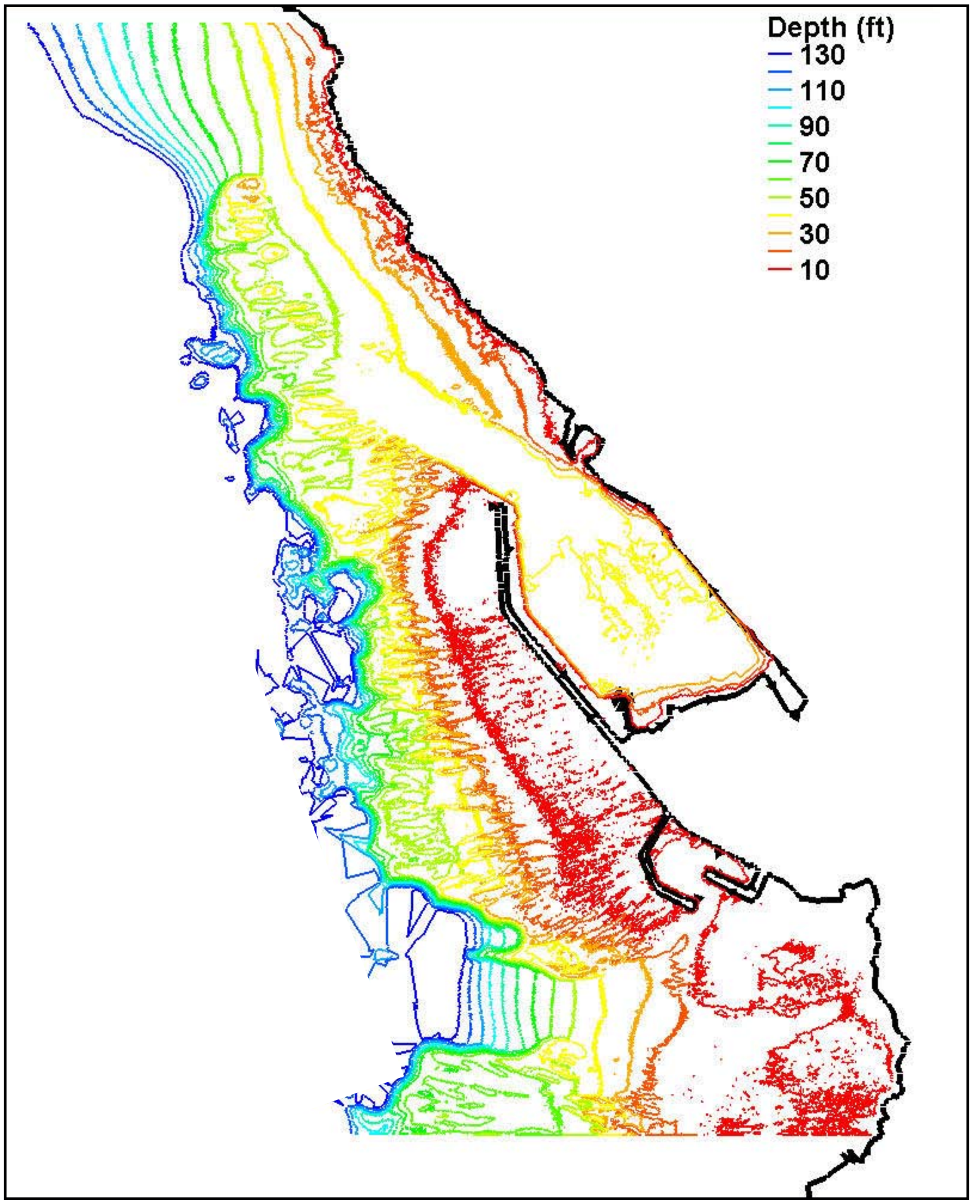

Figure 25. SHOALS bathymetric contours and coverage area

A unit significant wave height and representative range of peak wave periods and peak wave directions were modeled, based on the Kawaihae Bay station wave climate. The T_p ranged from 8 sec through 20 sec, in 2-sec increments. The θ_p ranged from 225° through 315° azimuth (direction from which the waves come). Every combination of the three wave parameters was modeled in STWAVE, giving a total of 70 wave conditions. For each STWAVE input height/period/direction combination, SMS was used to generate a directional wave spectrum in 130-m (426-ft) depth. Spectral frequencies ranged from 0.04 Hz to 0.34 Hz in 0.01-Hz intervals. Spectral direction components covered ±85° from normal incidence to the grid, in 5° increments. The water level was mllw.

As with the island-scale application, STWAVE output was extracted at selected stations and further processed to compute transformation table ratios relating incident wave conditions to the selected output station. These results are discussed in the following section.

Wave Climate at Kawaihae Harbor

Wave climate at deep draft harbor outside gauge location

Model results for the station nearest the location of the wave gauges outside Kawaihae Deep Draft Harbor are shown in Figures 26-28. Only the months January through March are included because the field gauges only operated during those months. The percentage of calms was 17.6 percent. The H_s rose shows waves coming primarily from the narrow arc 260-280°. The relatively broad spread of wave directions at the offshore Kawaihae Bay station has collapsed to a narrow range due to refraction over shallow nearshore bathymetry. Wave directions are approximately centered on 270°, perpendicular to the local bathymetric contours. The percent occurrence plots show that θ_p is confined to the range 240-290°. The highest H_s value has dropped to 2.9 m (9.6 ft).

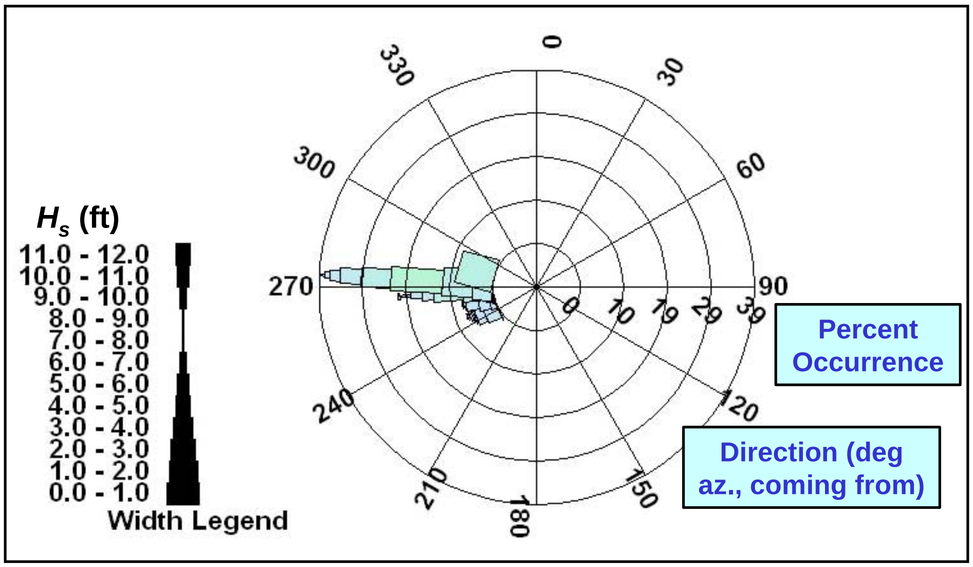

Figure 26. Wave height rose for STWAVE station coincident with Kawaihae outside gauges, Jan-Mar 95, 17-m (55-ft) depth

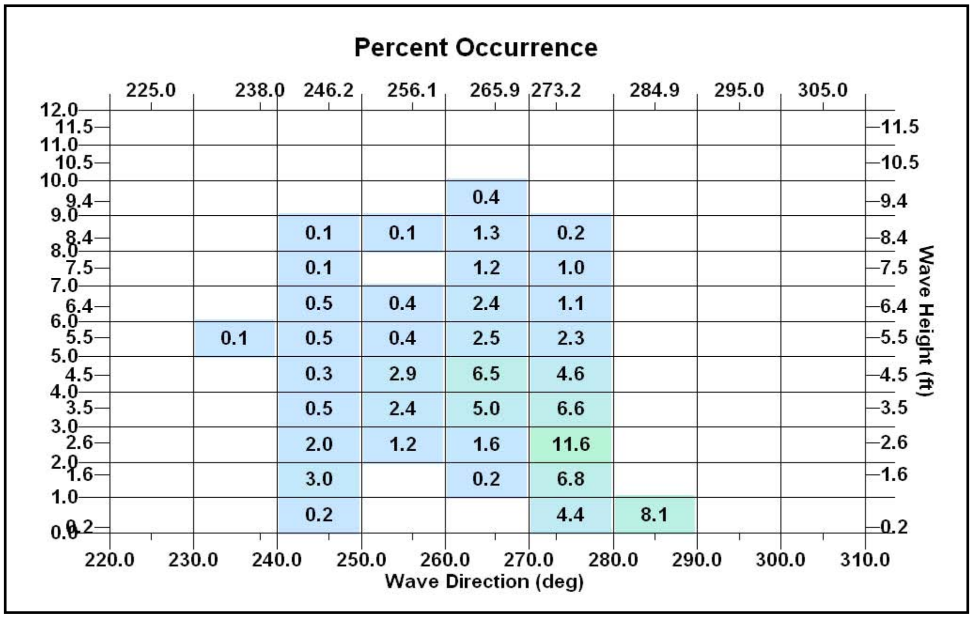

Figure 27. Percent occurrence, H_s vs. θ_p, for STWAVE station coincident with Kawaihae outside gauges, Jan-Mar 95, 17-m (55-ft) depth

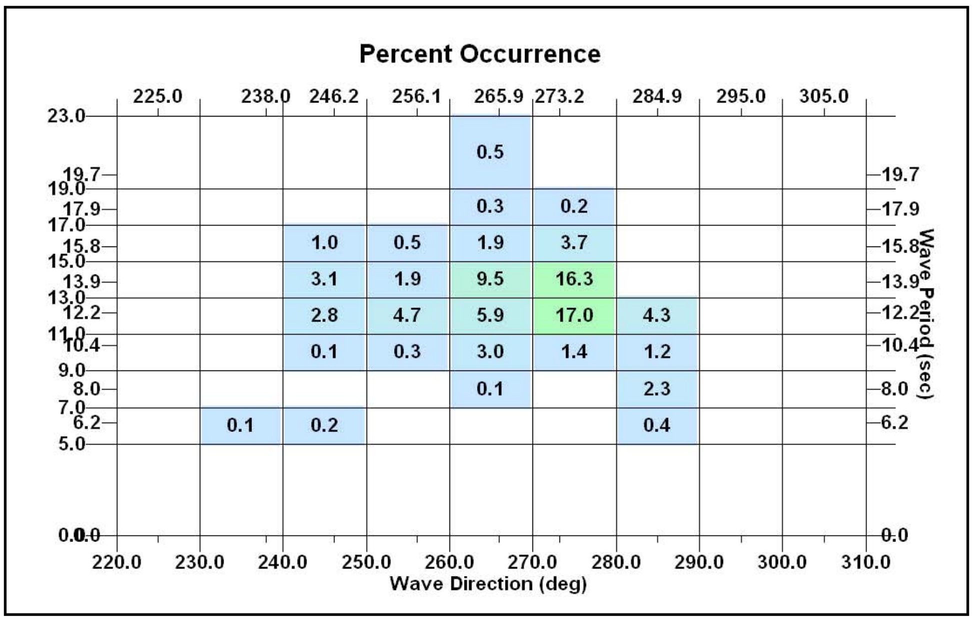

Figure 28. Percent occurrence, T_p vs. θ_p, for STWAVE station coincident with Kawaihae outside gauges, Jan-Mar 95, 17-m (55-ft) depth

Wave climate results for the co-located wave gauges outside Kawaihae Deep Draft Harbor are nearly the same, so only one gauge is presented here (Figures 29-31). The H_s rose shows a strong similarity to that produced by modeling, with waves coming almost exclusively from the narrow arc 260-280°. The percent occurrence plots show a general similarity to the model results, but several differences are evident. The gauge H_s tends to be lower than model H_s in the key 260-280° direction range. Maximum H_s is about 0.9 m (3 ft) lower. Median H_s in each band is 0.3-0.9 m (1-3 ft) lower, but this tendency is strongly influenced by the treatment of calms in the model results. The H_s is set to zero for calms in the model results, whereas there is always some level of wave activity outside Kawaihae Harbor. When the offshore buoys suggest calm conditions (waves propagating away from the harbor), H_s outside the harbor is expected to be low, but could easily be up to 0.3 m (1 ft) or more. Thus, the gauge results show a very high percentage of waves in the 0.3-0.6-m (1-2-ft) band, relative to the model results. For harbor alternative evaluation, this under-representation of 0.3-0.6-m (1-2-ft) H_s cases is not a concern, as these wave conditions do not cause navigation and mooring problems in the harbor.

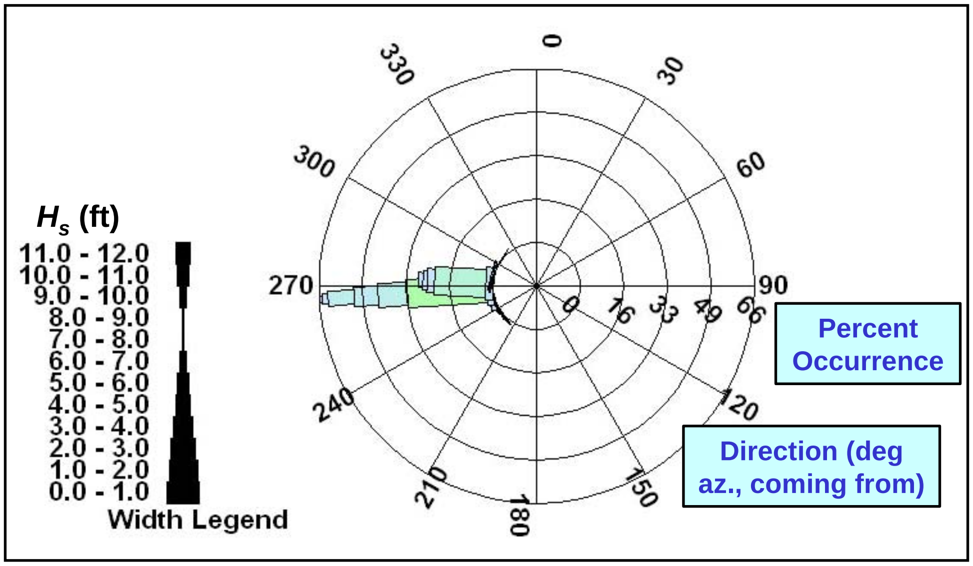

Figure 29. Wave height rose for Kawaihae outside gauges, Jan-Mar 04, 17-m (55-ft) depth

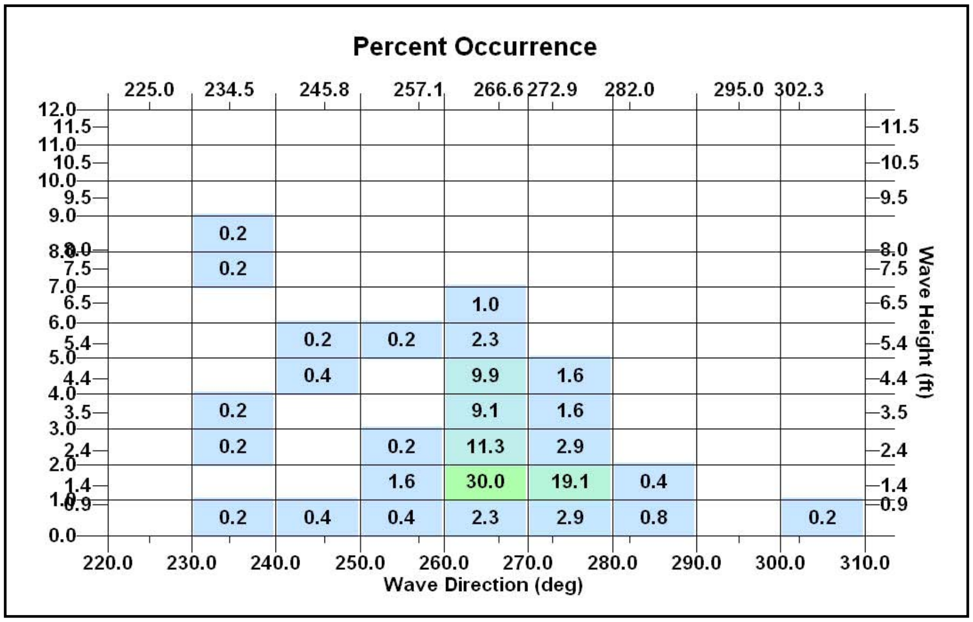

Figure 30. Percent occurrence, H_s vs. θ_p, for Kawaihae outside gauge 0388, Jan-Mar 04, 17-m (55-ft) depth

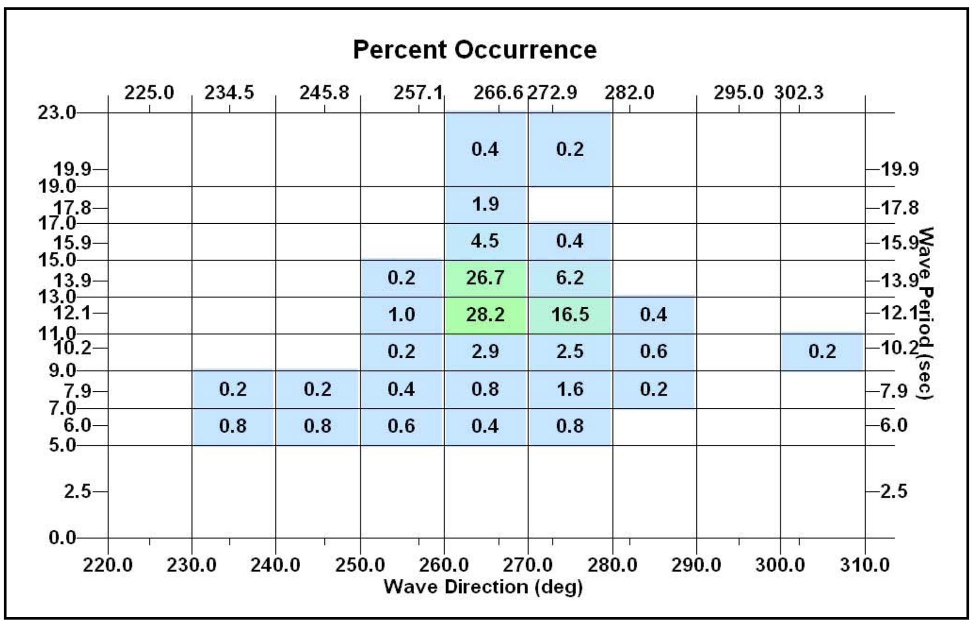

Figure 31. Percent occurrence, T_p vs. θ_p, for Kawaihae outside gauge 0388, Jan-Mar 04, 17-m (55-ft) depth

Also, the gauge shows a greater presence of H_s occurrences coming from 230-240°, including a maximum H_s of 2.4 m (8.0 ft). The percent occurrence plot for T_p versus θ_p strongly resembles the model result. The T_p values in the dominant 260-280° bands are mainly between 11 and 15 sec, with full range of about 6-20 sec in both gauge and model summaries. The gauge T_p values in the 230-240° band, where the maximum H_s occurred, are relatively short, 5-7 sec. This evidence and examination of weather maps at the time when the highest waves were recorded at the gauge indicate that these waves were generated by a local storm event.

This comparison of model and gauge results leads to two key conclusions. First, the model appears to give a reasonable representation of the general wave climate at the gauge, especially considering that the summaries cover a relatively short 3-month duration from different years. Differences in wave climate details would be expected in such a comparison. Second, the gauge recorded high waves from the southwest due to a local storm. This type of event may not be sufficiently represented in the buoy data, although some are evident in the full year Dec 94-Nov 95 climate. Recent WIS hindcasts help to evaluate this aspect of wave climate. From WIS station 114, which is near the buoy 51027 location, 4.8 percent of hindcasts during 1995-2004 came from 220-260° azimuth (vector mean direction at peak frequency) vs. 4.6 percent during the single year 1995. For H_s less than 1.8 m (6 ft) from 220-260° azimuth, the 10-yr and 1-yr WIS climates were virtually identical. For H_s greater than 1.8 m (6 ft) from 220-260° azimuth, the 10-yr climate had 0.3 percent of the hindcasts (with maximum H_s of 3.0 m (9.7 ft)) vs. 0.05 percent (with maximum H_s of 1.9 m (6.2 ft)) in the 1-yr climate. Thus, there may be a small under-representation of severe, but relatively infrequent wave events from 220-260° azimuth. If any harbor alternatives are especially vulnerable to high waves from the southwest, special care should be taken to ensure these waves receive adequate consideration.

Incident wave climate for CGWAVE modeling

Incident wave climate for CGWAVE modeling is needed at an offshore point that is representative of the location and depth along the CGWAVE seaward boundary. This point is shoreward of the Kawaihae Bay wave climate station but seaward of the Kawaihae Deep Draft Harbor entrance channel and outside gauge location. A station to represent CGWAVE incident wave conditions was designated in the local STWAVE grid due west of the harbor entrance in 88-m (289-ft) water depth. Wave climate results for the full year Dec 94 through Nov 95 are presented in Figures 32-34. They are similar to the Kawaihae Bay station summaries, but an early stage of wave direction collapse toward the range 260-280° is evident in the station for CGWAVE. For example, the frequently-occurring low waves coming from 310-350° azimuth at the Kawaihae Bay station (Figure 21) have collapsed into 300-310° azimuth at the CGWAVE boundary (Figure 32).

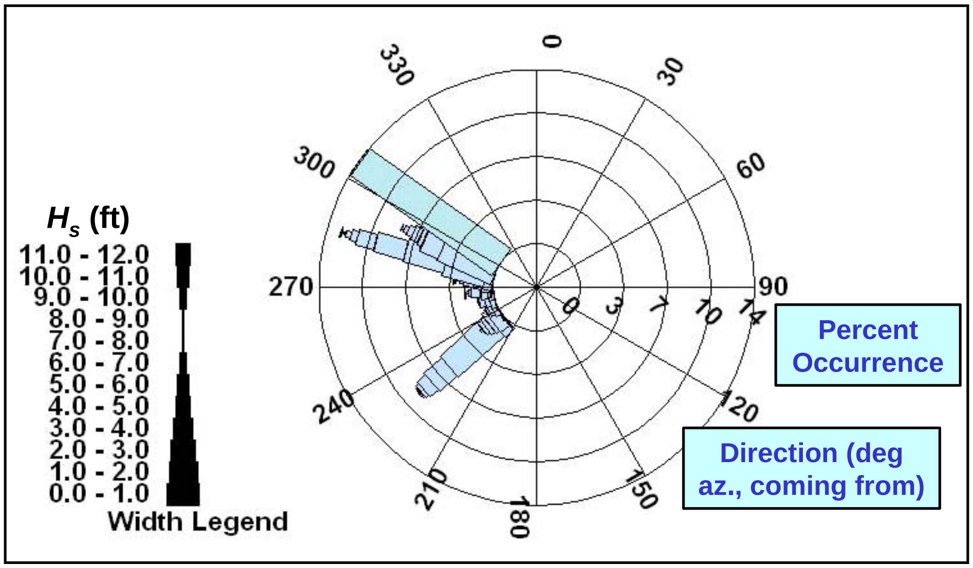

Figure 32. Wave height rose for STWAVE station to match CGWAVE seaward boundary, Dec 94-Nov 95, 88-m (289-ft) depth

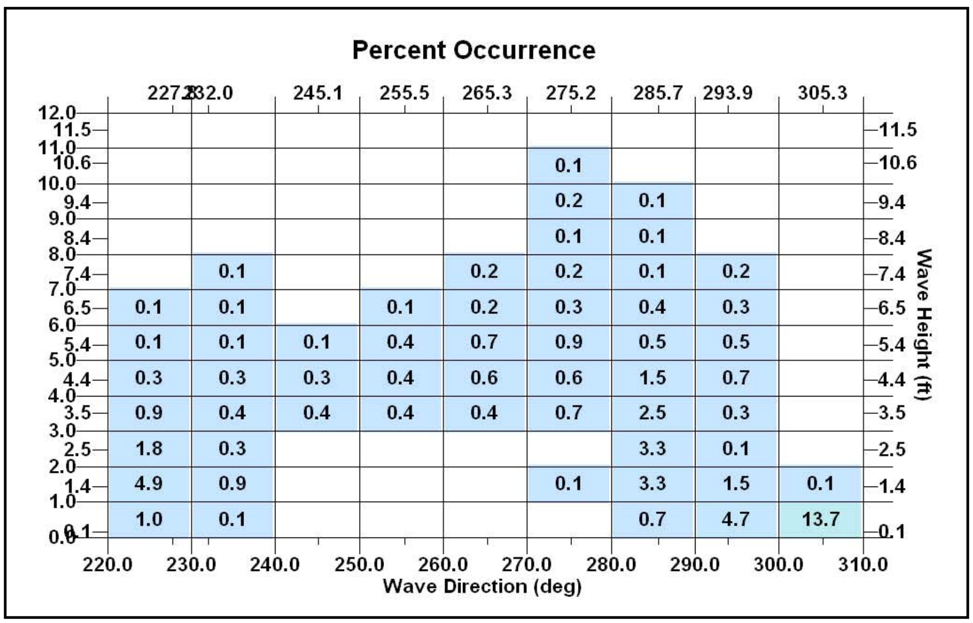

Figure 33. Percent occurrence, H_s vs. θ_p, for STWAVE station to match CGWAVE seaward boundary, Dec 94-Nov 95, 88-m (289-ft) depth

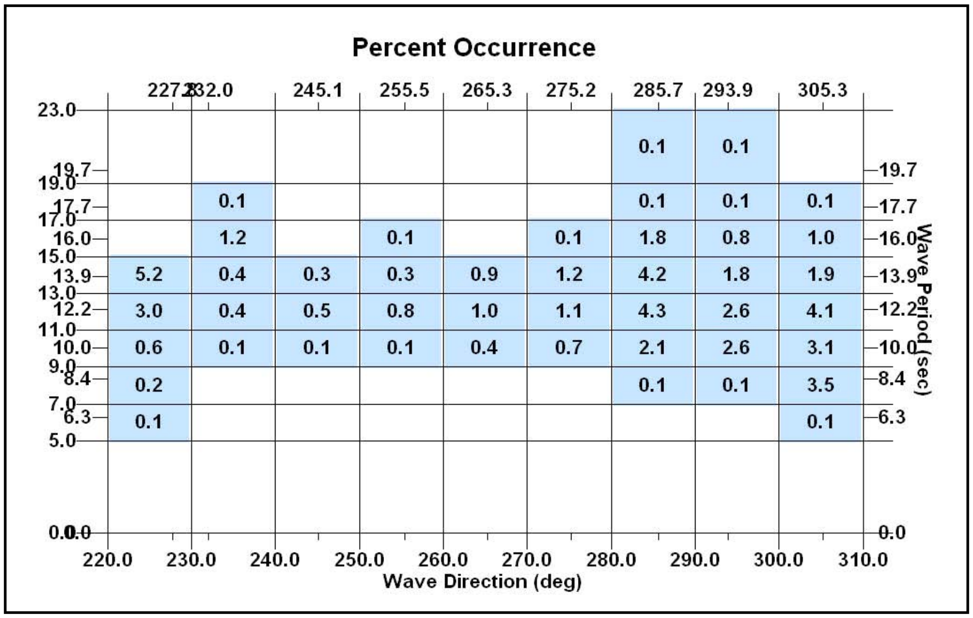

Figure 34. Percent occurrence, T_p vs. θ_p, for STWAVE station to match CGWAVE seaward boundary, Dec 94-Nov 95, 88-m (289-ft) depth

3 Numerical Model for Harbor Waves

Objectives and Approach

The numerical model for harbor waves studies had two main objectives:

- Calibrate and validate the numerical model with physical model and field data.

- Use the numerical model to evaluate the effect of proposed harbor modifications on harbor wave response.

The numerical model used for the studies, CGWAVE, is the standard CHL tool for numerical harbor wave investigations. The model includes the following assumptions:

- No wave transmission through breakwaters.

- No wave overtopping of structures.

- Structure crest elevations above the water surface cannot be tested or optimized.

- Currents in the channel cannot be evaluated.

- Diffraction around structure ends is represented by diffraction around a blunt vertical wall with specified reflection coefficient.

Despite limitations imposed by the aforementioned assumptions, CGWAVE is considered suitable for meeting the numerical modeling objectives of the Kawaihae Deep Draft Harbor wave response study.

The harbor wave response model is described in the following section, including a general description of the CGWAVE model and implementation of the model at Kawaihae Deep Draft Harbor. The next two sections cover model calibration and validation. Validation was accomplished in two steps. First, the model was validated relative to physical model data collected nearly 40 years ago. Second, the model was calibrated and validated with a combination of storm wave events selected from recent field data. The final section of this chapter describes the test procedures and calculations.

As part of the test procedures, a suite of incident wave conditions must be specified at the seaward boundary of the area covered by CGWAVE. Incident short waves are determined by consideration of the wave climate developed in the previous chapter. Incident long waves are specified over a broad range of frequencies, but only a normally-incident direction, to identify possible harbor resonant responses.

The existing harbor and six proposed modifications were studied. Results for wind waves and swell are presented in Chapter 4. Harbor oscillation results are presented in Chapter 5. The presentation focuses on wave conditions in the vicinity of existing or proposed piers, but results over the full harbor area are also given.

Model Description

Model formulation

The numerical wave model CGWAVE is a steady state finite element model used in the calculation of wave response in harbors of varying size and depth. It may also be applied along open coastal regions, at coastal inlets, around islands, and around fixed or floating structures. CGWAVE simulates the combined effects of wave refraction and diffraction included in the basic mild-slope equation. It can also include effects of wave dissipation by friction, breaking, nonlinear amplitude dispersion, and harbor entrance losses. The basic model deals with regular waves, but irregular (spectral) wave conditions can be simulated by combining regular wave results.

Several fundamental, theoretical, and computational advances are included in the model. The open boundary condition (seaward boundary of the model domain) is treated with a new parabolic approximation method along with the classical super-element technique. An efficient iterative procedure (conjugate gradient method) is used to solve the discretized model equations, enabling the model to be used practically for larger domains.

The CGWAVE model is interfaced with commercially available U.S. Army Corps of Engineers-supported software to assist in preparing model grids and other inputs and in displaying model results. This software-assisted pre- and post-processing is needed in any practical application.

More information on CGWAVE is available from Demirbilek and Panchang (1998) and from the model Internet web site (*http://chl.wes.army.mil/research/wave/wavesprg/numeric/wentrances/cgwave.htp*). The software package for pre- and post-processing is part of the Surface-Water Modeling System (SMS). The SMS software is also described through the model Web site.

Finite element grids

Bathymetric data for Kawaihae Deep Draft Harbor and surrounding area are available in the NOAA GEODAS database described previously. Very detailed nearshore bathymetric points are available from the Scanning Hydrographic Operational Airborne Lidar Survey (SHOALS) surveying system. Surveys, funded by the Honolulu District, were available during the year 2000. NOAA National Ocean Service (NOS) hydrographic chart 19330 provides a visual check to insure that GEODAS and SHOALS are free of erratic bathymetric points in the study area. SHOALS appears to give accurate, detailed coverage of areas inside and outside the harbor out to a depth of about 35 m (115 ft), including excellent definition of reef and channel areas.

The numerical model seaward boundary is a semicircle (Figure 35). This boundary is normally extended far enough seaward to encompass complex near-shore bathymetry, including reefs, shoals, and channels. However, the number of grid elements and model run time increases as grid coverage area increases. The final grid is a balance between covering key parts of the study area, while maintaining a workable grid size. For this study, the grid extended seaward to a depth of about 45 m (148 ft).

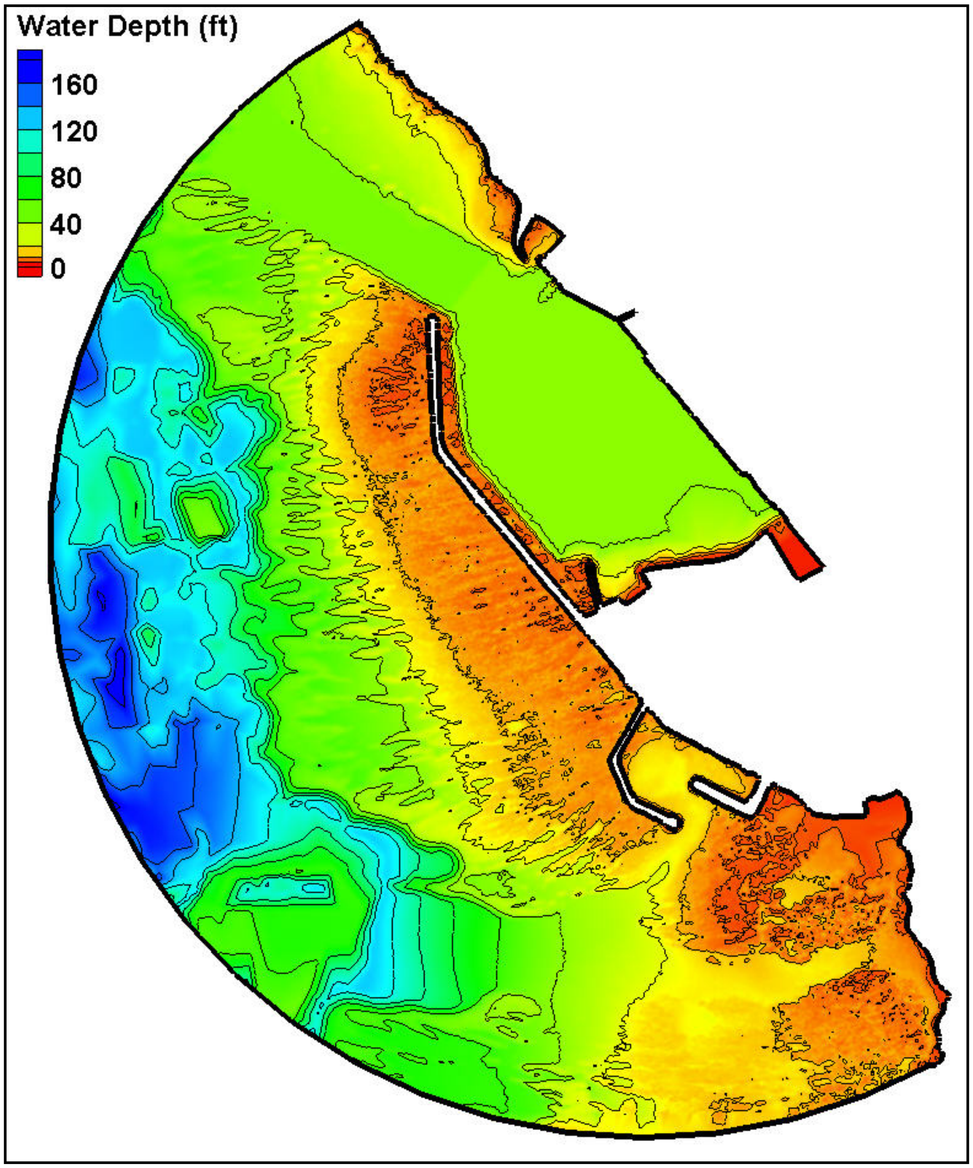

Figure 35. CGWAVE grid coverage area and bathymetry, existing harbor

A finite element grid of the existing harbor was constructed over the model domain. Grid element size is based on the needed model resolution for the shortest period waves in the shallowest water depth of concern in the study. For the longer period waves, the grid gives a high degree of resolution. Grid characteristics are summarized in Table 4. Bathymetric data from SHOALS and other sources discussed previously were transferred onto the finite element grid. The SMS software was used for all bathymetry and grid development.

Table 4 CGWAVE Grid Sizes				
Harbor Plan	**Elements**	**Nodes**	**Semicircle Boundary Nodes**	**Length of Typical Element (ft)**
Existing	243458	123507	583	26
Plan 1a	242029	122831	583	26
Plan 2a	242600	123079	583	26
Plan 2b	243500	123540	583	26
Plan 3	243551	123564	583	26
Plan 4	242671	123111	583	26
Plan 5	237247	120371	583	26

Reflection coefficients, K_r, are needed for all solid boundaries. For the short wave tests, K_r values were estimated based on model validation tests with field data along with existing U.S. Army Corps of Engineers guidance, photos and field notes from a site visit by CHL personnel, and past experience. The solid boundary was divided into 18 zones and a reflection coefficient was estimated for each zone (Figure 36). Reflection coefficients range from 0.2 for the shallow sandy beach along the southwest shore of the existing harbor to 0.5-0.6 for pier areas and 0.8 for the grouted revetment immediately northwest of the Transpacific Pier. Reflection coefficients for shorelines extending beyond the harbor on either side were set to 0.35-0.40 for shoreline encompassed by the grid domain and 0.0 for shoreline beyond the grid domain. Bottom friction was set to zero. Additional parameter values used in the numerical model are summarized in Table 5.

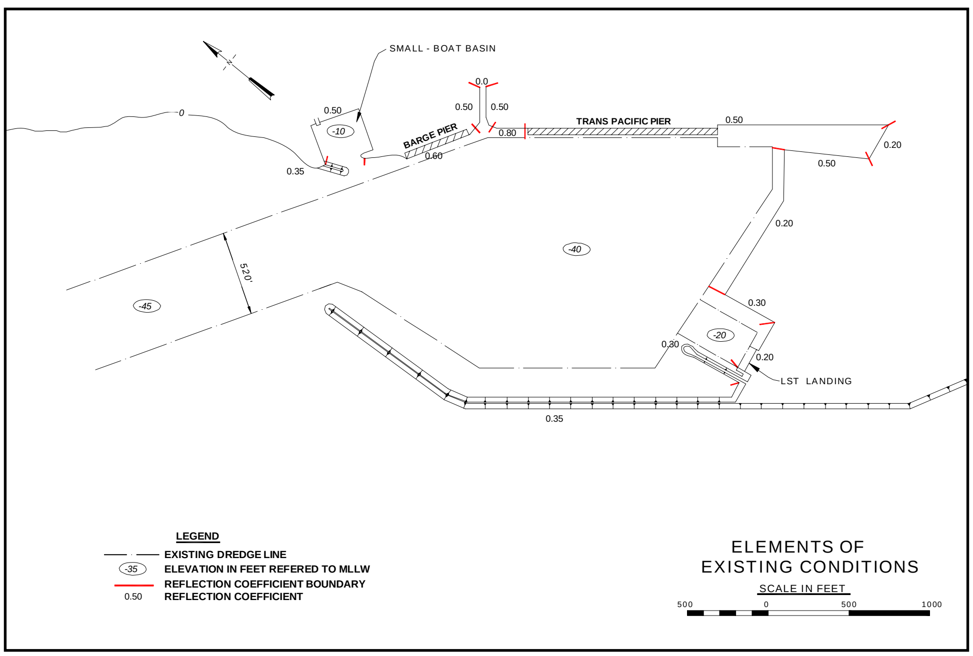

Figure 36. Model wave reflection coefficients, short waves, existing harbor

Table 5
Parameter Values Used in CGWAVE

Parameter	Value	
	Short Waves	Long Waves
Number of terms in series	35	35
Maximum number of iterations for convergence	500,000	500,000
Maximum number of iterations for nonlinear mechanisms	10	10
Bottom friction	0.00	0.02
Wave breaking	off	off
Nonlinear dispersion	off	off
Exterior reflection (shore boundaries outside grid domain)	0.0	0.0
Tolerance for equations	10^{-9}	10^{-9}
Tolerance for nonlinear mechanisms	10^{-4}	10^{-4}
Semicircle orthogonal orientation, deg counterclockwise from +x axis (0=east, 90=north, 180=west)	208.6	208.6

Different parameters are used for the long wave tests. The reflection coefficient was set to 1.0 for all boundaries, since long waves generally reflect very well from a coastal boundary. Long waves are more affected by bottom friction than short waves, so a value greater than zero is appropriate. The value is best determined by calibration with field data. A value of 0.02 was selected, based on calibration tests for Kahului Harbor described by Thompson and Demirbilek (2002). This and other parameters are summarized in Table 5.

In addition to existing conditions, six harbor modification plans were specified for evaluation, as discussed in Chapter 1. The existing harbor grid boundaries and bathymetry were modified to match the alternative plans (Figures 37-42). Grid characteristics for each configuration are included in Table 4. Plan 1a is given as representative of the various Plan 1 grids. Short wave reflection coefficients were modified as appropriate for the plan grids. The general guideline was K_r= 0.35 along breakwater structures.

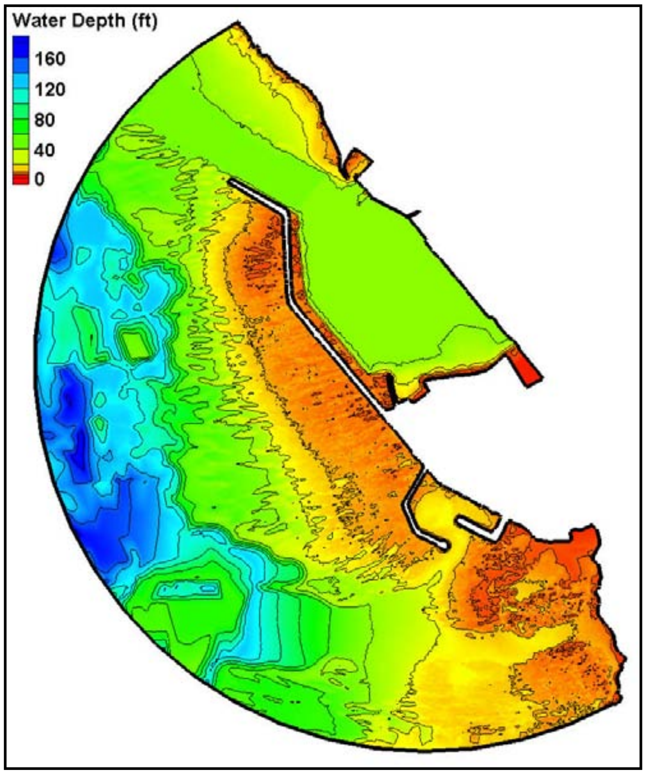

Figure 37. Model bathymetry, Plan 1a

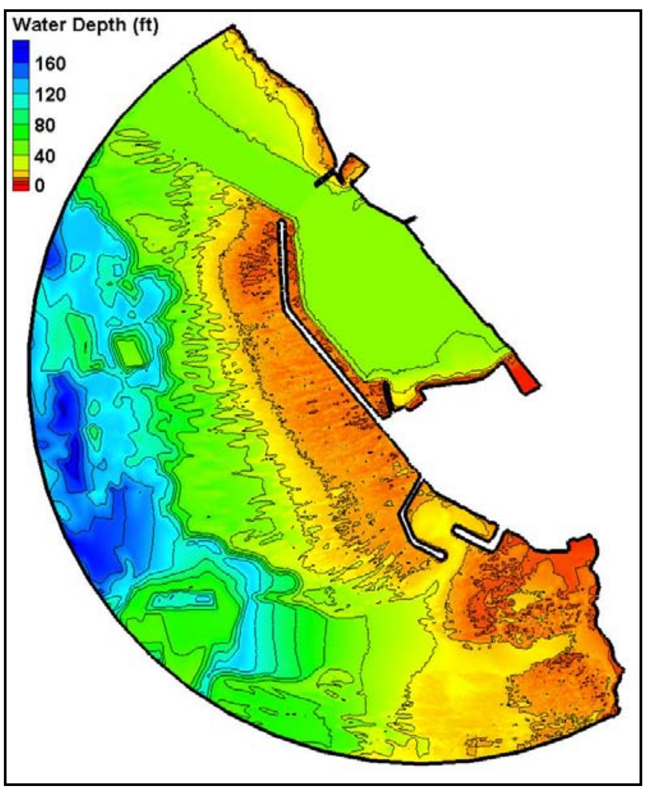

Figure 38. Model bathymetry, Plan 2a

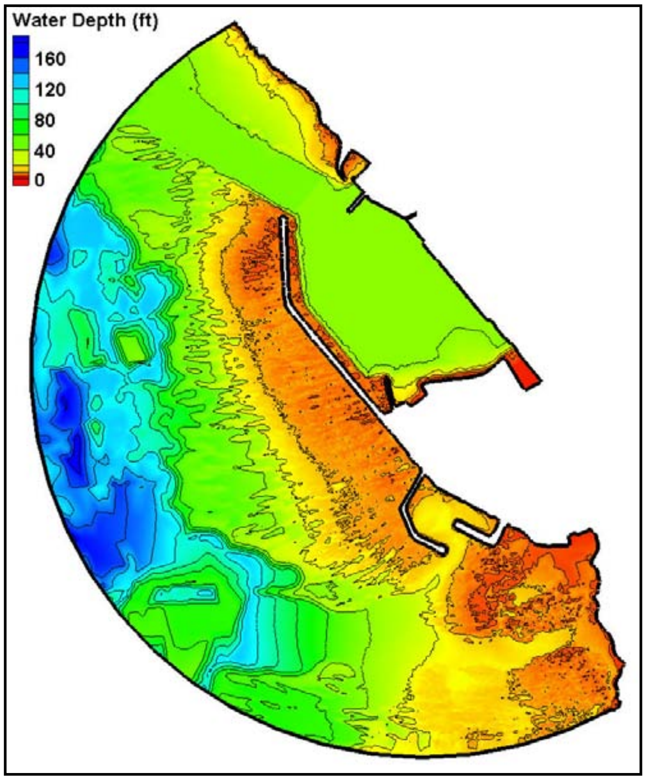

Figure 39. Model bathymetry, Plan 2b

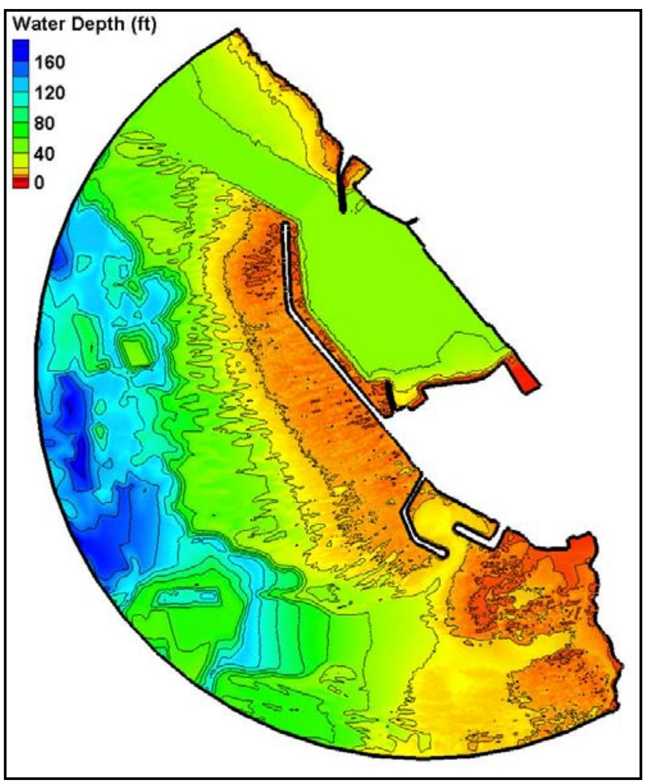

Figure 40. Model bathymetry, Plan 3

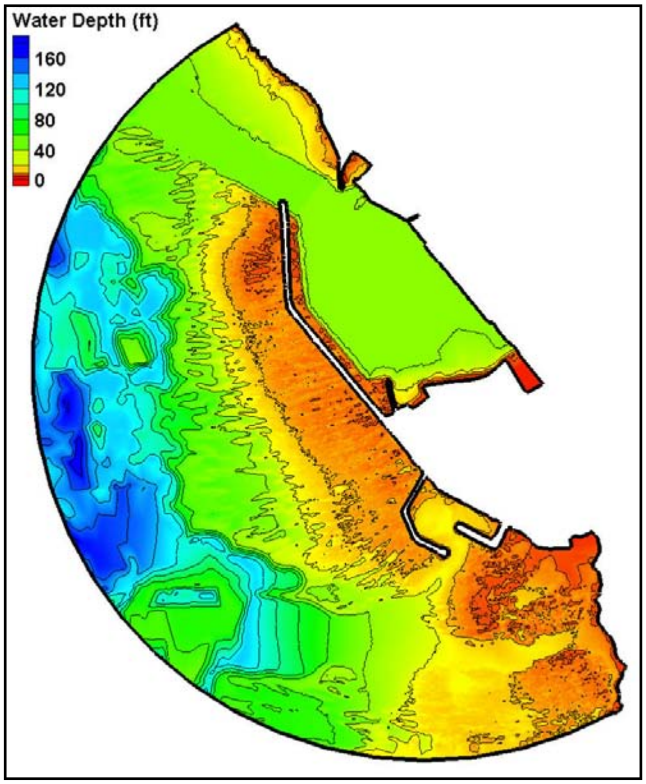

Figure 41. Model bathymetry, Plan 4

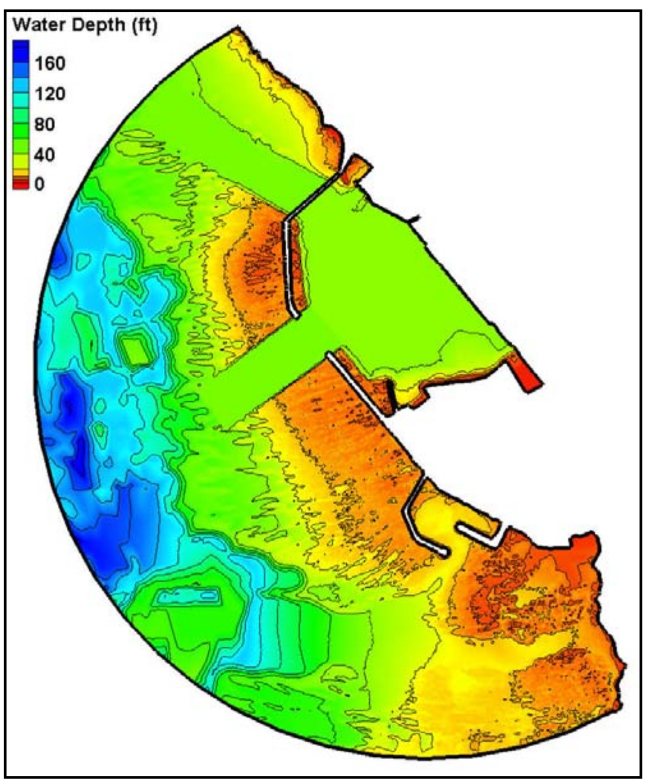

Figure 42. Model bathymetry, Plan 5

Model Validation to Physical Model Data

A physical model study of Kawaihae Deep Draft Harbor was conducted previously by ERDC (Brasfeild and Chatham 1967). Although this study was performed many years ago, the modeling tools and approach used are still considered a reliable basis for design. The biggest limitation is that model test conditions at the time of study were exclusively regular waves. Present-day physical model tests often use irregular wave conditions that are more representative of natural ocean waves. Despite this limitation, it was considered worthwhile to validate CGWAVE with the physical model tests.

A CGWAVE grid was developed to match the physical model layout shown in Figure 43. This physical model Plan 4A most nearly matches the present prototype harbor. The availability of only regular wave tests in the physical model is a major limitation for calibration. Numerical models such as CGWAVE typically exaggerate periodic spatial variations in waves when applied with regular waves over prototype bathymetry. Numerous comparisons were run between CGWAVE and the physical model to evaluate effects of incident wave parameters, boundary reflection coefficients, and wave breaking parameters. Some numerical model tests with narrow uni-directional and multi-directional spectra were also run. Water levels in the CGWAVE runs matched water levels used in physical model testing. Example results are shown in Figure 44. Although some of the comparisons are reasonably good, none provided a uniformly good match to the physical model gauge data. The difficulty in getting a good validation at all gauges was attributed primarily to the regular wave testing. Since the ultimate objective of this project was to evaluate alternative plans for the prototype harbor in response to multi-directional waves over prototype bathymetry, further conclusive validation to physical model tests was not warranted. Prototype wave data were to be the basis for final calibration and validation of CGWAVE.

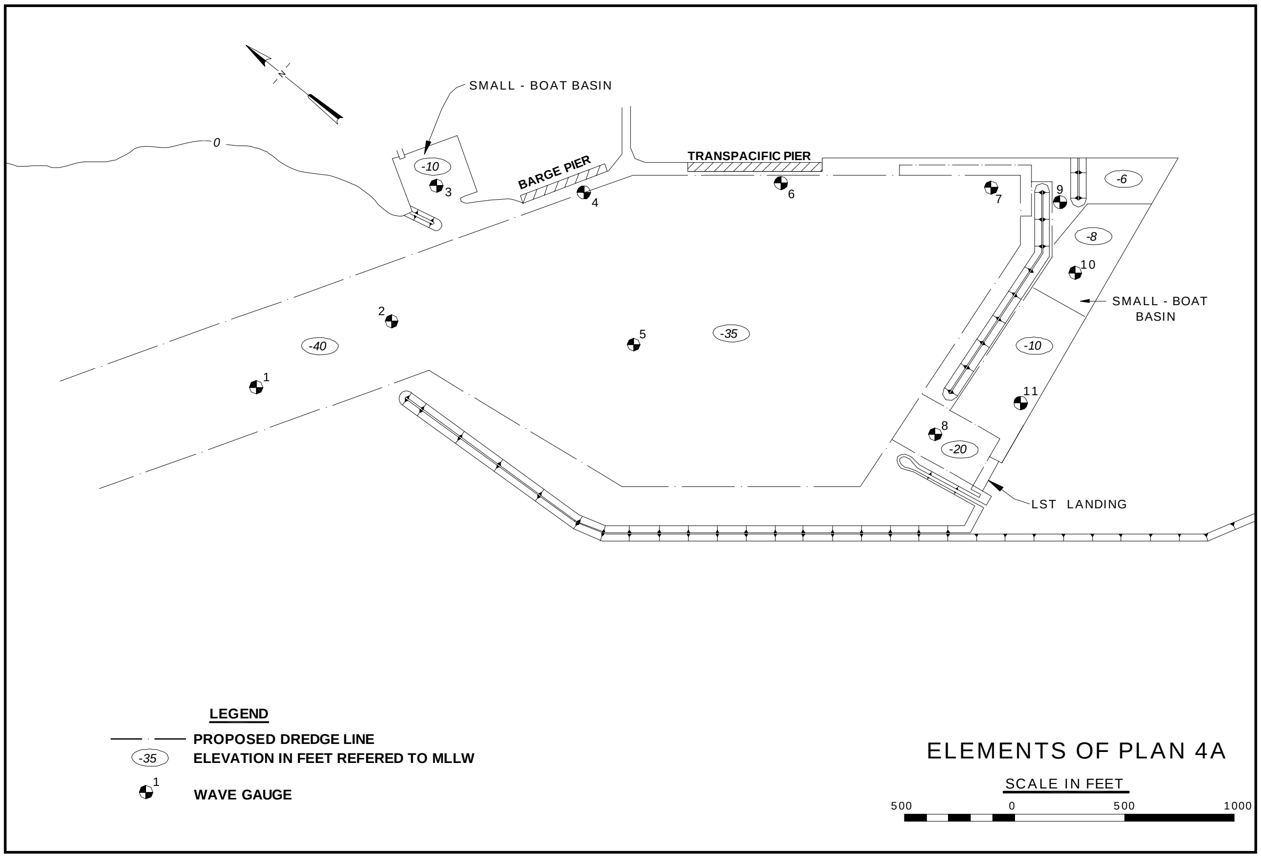

Figure 43. Physical model layout

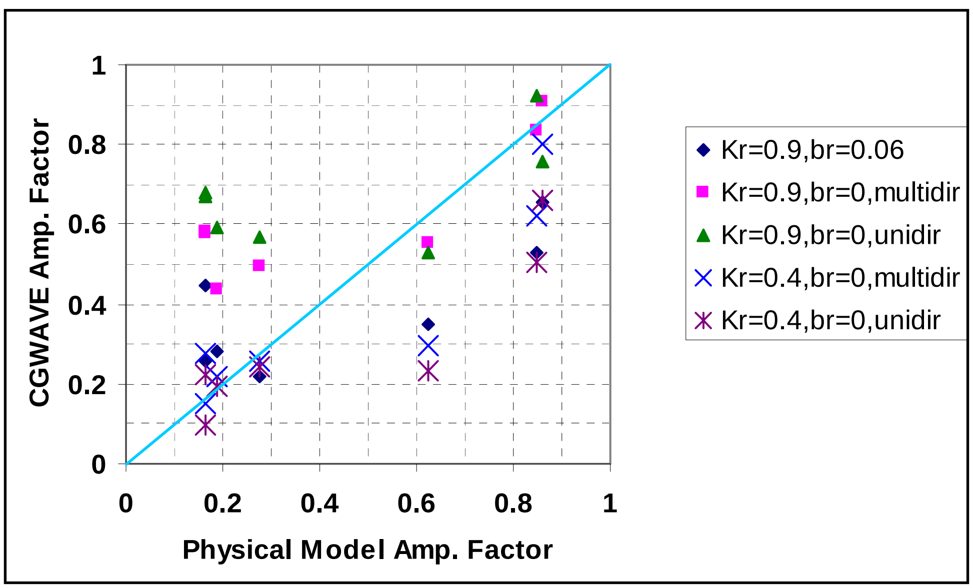

Figure 44. Comparison of CGWAVE and physical model amplification factors (ratio of local wave height to incident wave height). “Kr” denotes boundary reflection coefficient, “br” denotes wave breaking parameter, “multidir” denotes multi-directional spectral waves, and “unidir” denotes uni-directional spectral waves

Model Validation to Field Data

Five high wave events during February 2004 were used for short wave calibration and validation (Table 6). These events give a variety of T_p and peak wave direction, θ_p, values affecting Kawaihae Deep Draft Harbor. Incident wave conditions for these events were measured at the co-located directional POH gauges at the seaward end of the entrance channel (Figure 11). The POH gauges recorded at 3-hr intervals, and recording times were staggered so that one outside and one inside gauge activated every 1.5 hrs. The modeled events were selected to try to capture a time period when incident wave conditions were relative steady during the approximately 2-hr time interval needed to get records from all four gauges. The two recording times used for model calibration and validation are shown in the table for each event.

Table 6
Field Cases for Short Wave Model Calibration, POH Gauges Outside Harbor Entrance

Event	Date	Hour	H_s, ft	T_p, sec	θ_p deg az., coming from
1	13 Feb 04	0830, 1000	5.8	12.9	268.5
2	20 Feb 04	1300, 1430	5.9	15.7	269.0
3	27 Feb 04	1600, 1730	8.0	6.0	235.4
4	28 Feb 04	1730, 1900	6.3	10.0 (14.5)	264.2
5	29 Feb 04	1900, 2030	6.8	14.5 (5.6)	268.5

Note: T_p values in parentheses also were evident in the gauge data, indicating the presence of more than one wave train. However, the T_p values in parentheses were not used for modeling.

Weather charts covering evolution of the five events helped clarify the origin of the high waves. Events 1, 2, and 4 are long period swell created by large-scale winter storms in the North Pacific, northwest of the Hawaiian Islands. The waves wrap around the Hawaiian Islands and approach Kawaihae from the west. Event 3 is short period locally-generated waves from southwest of Kawaihae. Event 5 appears to be a mixture of wave trains from both of these sources. These data help to validate the STWAVE island-scale model transformations in that: 1) northwest swell can wrap around the islands and produce high waves at Kawaihae approaching from the west, and 2) swell approaching the islands from the north is blocked and does not produce high waves at Kawaihae.

Since the model boundary in the directions of wave approach is significantly further seaward than the gauges, waves incident to the model need to account for small changes in wave height and direction that occur between the seaward boundary and the outside gauge location. Suitable incident wave conditions were determined by preliminary model runs.

The CGWAVE model was run with regular (monochromatic) waves for calibration to field data from the five events. Adjustments were made to the model grid, particularly boundary reflection coefficients, to optimize calibration of the model at the two inside gauge locations. After calibration was completed, a suite of wave components was generated for each storm event to approximate the directional spectrum of wave energy. CGWAVE was run for each suite of incident wave components and the output was post-processed to give spectral estimates at each harbor gauge location.

The calibrated model versus gauge H_s for the five events compares quite well for most cases (Figure 45). Maximum differences are 15 percent, except for Event 5. This event was the least suitable for validation. It consisted of sea and swell wave trains with very different periods, and only the swell component was modeled. While the outside gauges have H_s of 1.8 m (5.8 ft) or higher, gauges inside the harbor have H_s less than 0.9 m (3 ft) in all cases. The CGWAVE model effectively captured the dramatic decrease in H_s inside the harbor. This comparison was accepted as sufficient validation of CGWAVE for wind wave and swell applications at Kawaihae Deep Draft Harbor.

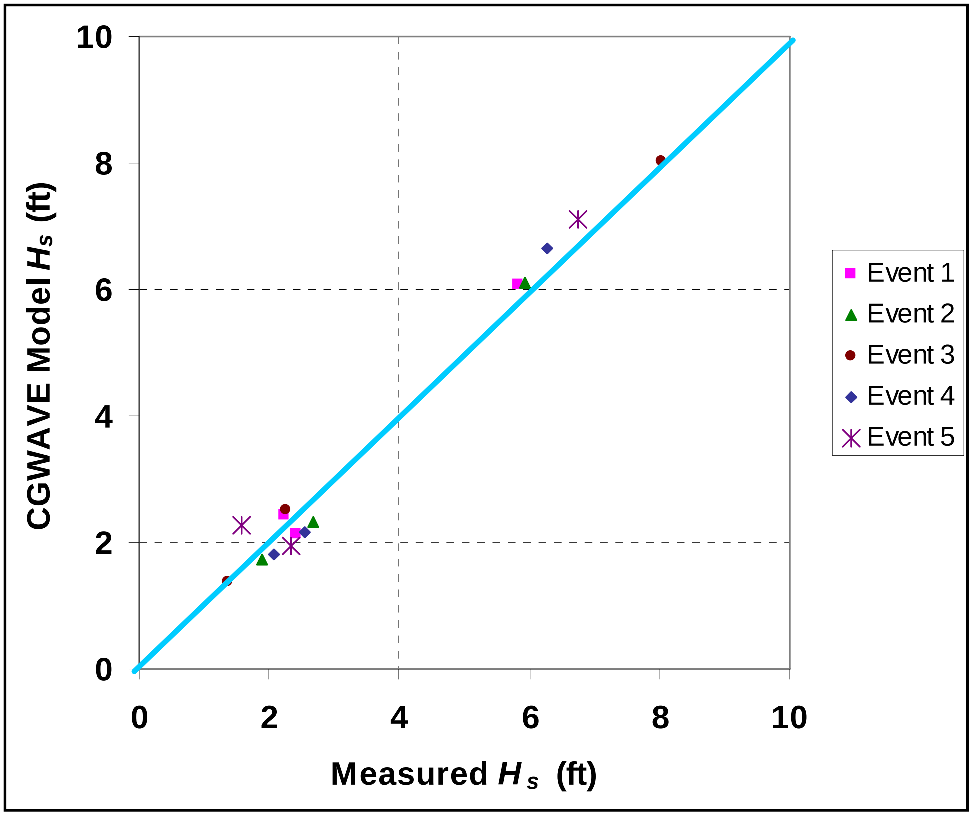

Figure 45. Model short wave calibration to five storm events

Differences between model and measured H_s in the above validation provide an estimate of the uncertainty associated with CGWAVE model results. Excluding Event 5, the mean and maximum differences between model and measurement are 8 and 15 percent. Thus, with known incident wave conditions, CGWAVE model H_s estimates inside the harbor can be considered to have an uncertainty of about plus or minus 10 percent.

Test Procedures and Calculations

Incident wave conditions

A range of short and long wave conditions incident to Kawaihae Deep Draft Harbor was considered. A representative range of wave periods and directions that could cause damaging waves inside the harbor was included, based on incident wave climate at the CGWAVE seaward boundary.

The short wave periods and approach directions considered are given in Table 7. These conditions provide reasonable coverage of the incident wave climate. The shortest wave period is representative of strong local storms. The longest period represents a very long swell condition. Directions were chosen to cover the full directional exposure of the harbor entrance, in 10° increments. These incident wave components can be expected to give a good representation of the directional spectrum in post-processing. Incident wave directions are illustrated in Figure 46.

Table 7
Summary of Incident Short Wave Conditions

Wave Period (sec)	Wave Direction (deg az., coming from)
6	220
8	230
10	240
12	250
14	260
16	270
18	280
20	290
22	300

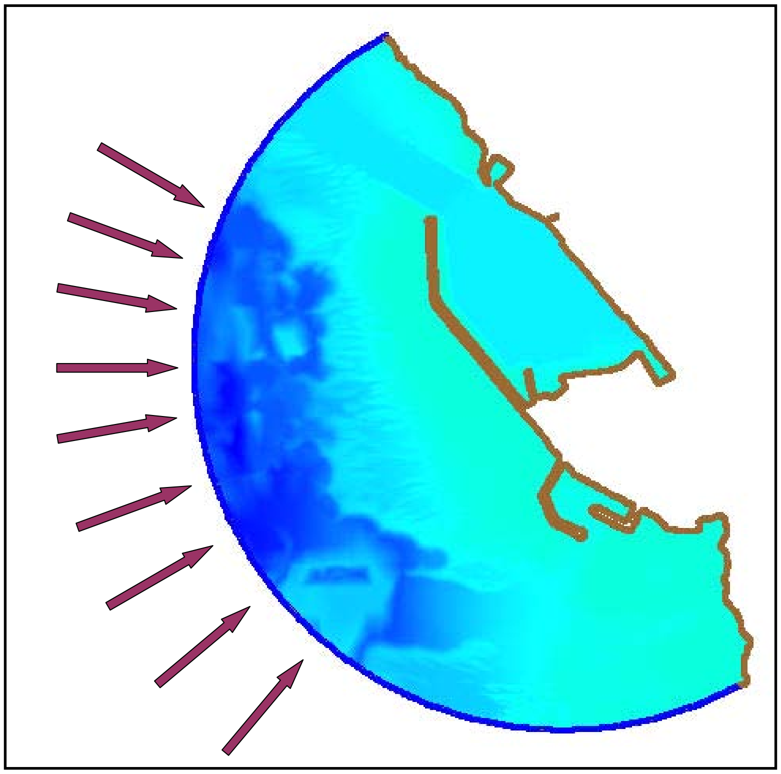

Figure 46. Incident short wave directions modeled

For the study of existing harbor conditions and comparison of alternatives, CGWAVE was run with the full set of short wave periods for directions 280-300° azimuth, in all possible combinations. For directions 240-270° azimuth, wave periods of 6-16 sec were run. For directions 220-230° azimuth, wave periods of 6-14 sec were run. These period ranges were considered sufficient to represent the incident wave climate. An incident wave height of 1 m was used for all runs. A total of 183 wave conditions were run. Model results were then properly weighted and recombined to represent each directional spectrum in the one-year incident wave time-history.

Incident long wave conditions considered are given in Table 8. A fine resolution in wave frequency was used over the full range of possible resonant conditions to ensure that all important peaks were identified. A total of 468 periods was considered. Only one approach direction is included, since past studies have indicated that harbor response is relatively insensitive to incident long wave direction. This direction, 270° azimuth, represents a relatively direct wave approach to the harbor entrance from deep water. The incident long wave height was 10 cm (0.3 ft), as was determined in previous studies for Kahului Harbor.

Table 8
Summary of Incident Long Wave Conditions

Wave Period (sec)	Wave Direction (deg az., coming from)
25.00	270
25.06	
25.13	
...[1]	
1000.0	

[1] Frequency increments are 0.0001 Hz for periods of 25-80 sec and 0.00006 Hz for periods of 80-1,000 sec.

One water level was tested. The tide range at Kawaihae Harbor is relatively small, with a range between mllw and mean higher high water (mhhw) of 0.6 m (2.0 ft). Harbor wave response is unlikely to vary much with water level over this tidal range. The water level was selected as mean lower low water, the reference datum for bathymetric data.

Calculation of spectra

Numerical model test results for short waves in Kawaihae Deep Draft Harbor are all based on spectral post-processing of the initial CGWAVE runs. Hence, short wave amplification factors are all in the form of $(A_{amp})_{eff}$ as described by Thompson et al. (1996). This approach requires, first, that CGWAVE be run with the range of wave periods and directions to be considered in the spectral calculations. Second, for each value of peak wave period, T_p , and wave approach direction, θ_p; a spectral peak enhancement factor, γ; and directional spreading factor, s, must be specified. The T_p and θ_p values were taken directly from the one-year incident wave time-history. Values for γ and s were approximated by the same procedure developed in the previous study. This procedure has been further tested and has become a standard approach in CHL spectral wave model studies. Thus, a one-year time-history of wind waves and swell can be reconstructed at any point in the model domain.

Output locations

In order to get special coverage of areas where harbor operations would most likely be affected by wind wave and swell conditions, output lines were selected to cover mooring areas along all piers in each harbor layout (Figures 47 and 48). The saving sequence began with the northwest end of the barge pier and proceeded clockwise around the harbor, as indicated in the figure. Further, an output line was designated along the center of the entrance channel, beginning at the seaward end, continuing through the breakwater gap and middle of the harbor basin, and ending near the intersection with the land boundary inside the harbor. Model results were saved at 20 equally-spaced points along each line segment. Since line segments differed in length, the spacing between points varied from 5 to 53 m (17 to 175 ft).

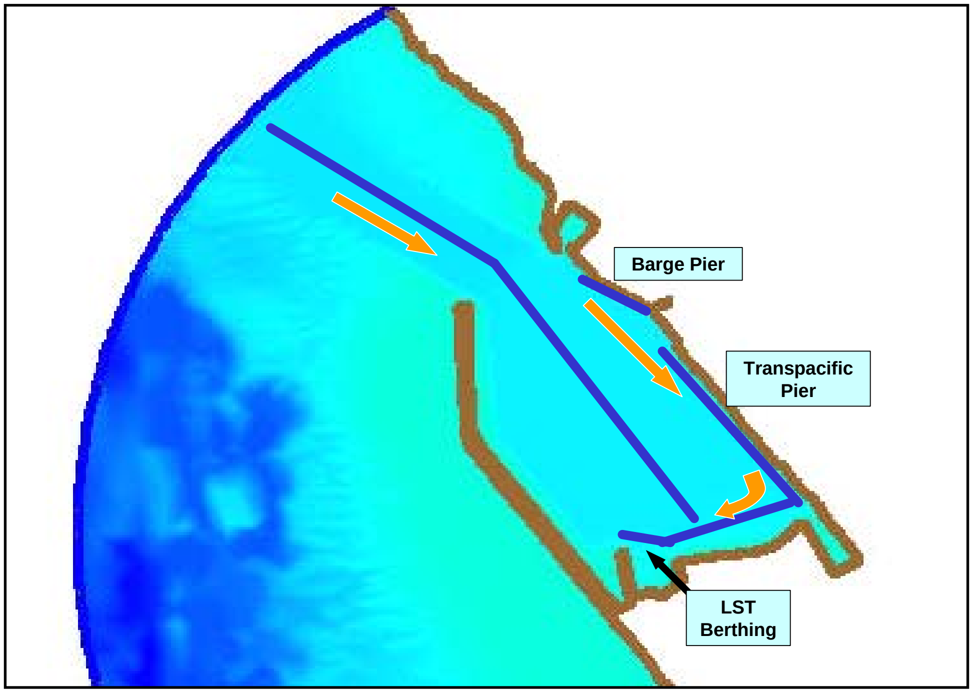

Figure 47. Model output lines, existing harbor and Plans 1, 2a, 2b, 3 and 4

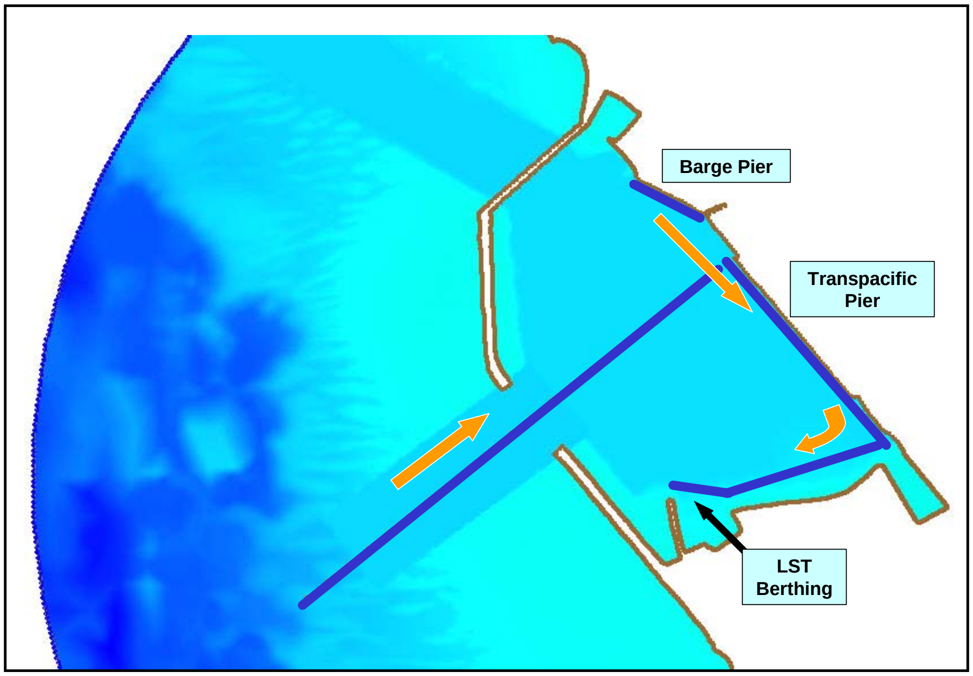

Figure 48. Model output lines, Plan 5

For long wave tests, 17 special output points were designated around the harbor to screen for possible resonance conditions. These points included three points along the barge pier, three points along the Transpacific Pier, two points in the LST landing area, and one point in the small boat basin opposite the harbor entrance.

4 Harbor Response to Wind Waves and Swell

Numerical model studies of the harbor response to wind waves and swell were directed primarily toward assessing the operational performance of alternative harbor modifications. Results, especially at existing pier areas, are summarized in this chapter. Amplification factors are discussed in the following section. The final section gives H_s values exceeded 10 percent and 1 percent of the time, a result more directly applicable to operational performance. The H_s values are derived from a combination of amplification factors from the CGWAVE numerical model and the one-year incident wave time history determined outside the harbor. They are compared to operational criteria for wind waves and swell.

Amplification Factors

Amplification factors, representing directionally-spread short wave spectra in the form of $(A_{amp})_{eff}$, were calculated for the variety of wind wave and swell conditions incident to Kawaihae Deep Draft Harbor during Dec 1994 through Nov 1995. Figure 49 illustrates amplification factor patterns over the harbor for a wave period and direction representative of some high wave events. Amplification factors are the ratio of local H_s to incident H_s. These displays represent a monochromatic wave condition. Although they show more spatial variations than a spectral wave condition, they are still helpful for illustrating general wave patterns in each harbor configuration.

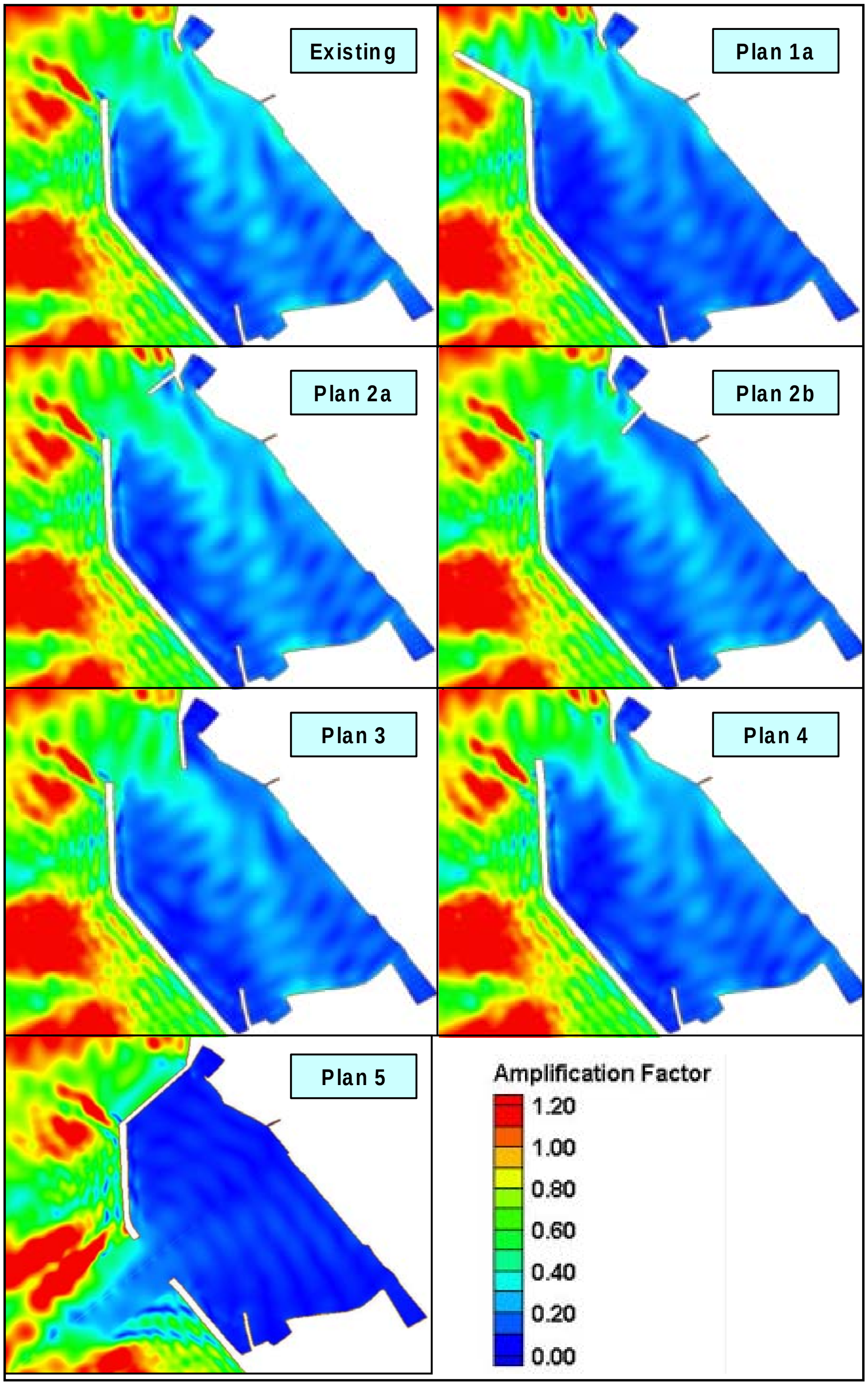

Figure 49. Wave height amplification factor, T = 14 sec, θ = 270° azimuth

Wave response of the existing harbor and the various plan harbors are shown. Since Plan 1a is sufficiently representative of the other Plan 1 variations for this illustration, Plans 1b, 1c, and 1d are not included. The amplification factor at any place in the harbor changes between plans only if there are significant changes in sheltering by breakwater structures. For example, the barge pier gains a small measure of protection from the seaward extension to the west breakwater in Plan 1a, but it gains substantial protection from the new stub breakwater just northwest of the pier in Plan 2b. Wind wave and swell response in the harbor is basically a result of diffraction through the breakwater gap. Boundary reflection characteristics have only a localized effect on the waves. Plan 5 provides exceptionally good protection throughout the harbor for this wave condition. However, Plan 5 is more vulnerable than the existing harbor and other plans to waves approaching from the southwest. The net result of this exposure is evident in the following section.

Evaluation against Operational Criteria for Wind Waves and Swell

Standard operational criteria used by USACE for wind waves and swell in shallow draft harbors are as follows:

- wave height in berthing areas will not exceed 0.3 m (1 ft) more than 10 percent of the time

- wave height in entrance and access channels and turning basins will not exceed 0.6 m (2 ft) more than 10 percent of the time

Standard criteria for wind waves and swell in deep draft harbors, such as Kawaihae Harbor, are not so well established. However, the criteria for shallow draft harbors can provide a useful basis for comparing alternative plans at Kawaihae Harbor. It has been used in previous deep draft harbor studies (e.g., Thompson and Demirbilek 2002). Experience with the Alaska ferry system (vessel lengths up to 91 m or 300 ft) suggests that the USACE 0.3-m (1-ft) criterion in berthing areas is a meaningful threshold for that application (Personal Communication, 2002, Harvey Smith, Department of Transportation and Public Facilities, State of Alaska). Additional information about criteria for a safe berthing area is summarized by PIANC (1995) and Thompson, Boc, and Nunes (1998). Briefly, PIANC (1995) recommends H_s less than 0.1-0.3 m (0.3-1.0 ft) with occurrence of not more than a few times a year for small craft and pleasure boats of length up to 20 m (66 ft). Criteria for larger vessels are expressed in terms of ship motion rather than waves. Thompson, Boc, and Nunes (1998), drawing on other published sources, give H_s less than 0.7 m (2.3 ft) for general cargo ships less than 30,000 DWT (dead weight), and wave height less than or equal to 0.6 m (2 ft) for comfortable U.S. Navy berthing area. Overall, the USACE criteria seem to provide a meaningful basis for evaluating harbor plans.

Another, perhaps more valuable criterion for evaluating pier areas under proposed harbor modifications is to compare with piers in the existing harbor. Many years of practical experience at existing piers can then be approximately transferred to new plans.

Wave heights for assessing the USACE criteria were computed by combining the time-history of incident wave parameters over the time period December 1994 through November 1995 with CGWAVE numerical model results to create a time-history of wave heights along each output line. For each observation time, the corresponding wave height at a harbor point is:

$$\left(H_s\right)_{harbor} = \left(A_{amp}\right)_{eff} \times \left(H_s\right)_{incident} \tag{2}$$

where

$(H_s)_{harbor}$ = significant wave height at a point in the harbor

$(A_{amp})_{eff}$ = spectral amplification factor calculated from model results for the periods and directions in Table 7 to represent incident T_p and θ_p

$(H_s)_{incident}$ = incident significant wave height

The 1-year time-history of $(H_s)_{harbor}$ at each point along the output lines was sorted into descending order and the value of H_s, which was exceeded 10 percent of the time, was identified. The H_s value exceeded 1 percent of the time was also identified. The H_s with 1 percent exceedance relates to a more demanding operational condition, which may be more applicable to some large commercial vessel facilities.

Results are presented and discussed in the following paragraphs. First, the four variations of Plan 1 are compared to determine an initial optimization for the Plan 1 breakwater extension length. Then the optimum Plan 1 is evaluated with other plan alternatives. Output lines are divided into five areas: 1) entrance channel, 2) mid-basin of harbor, 3) barge pier, 4) Transpacific Pier and small boat area along the shore extending southeast from the pier, and 5) south end of harbor and LST berthing area. Discussion is focused on H_s exceeded 10 percent of the time. Results for H_s exceeded 1 percent of the time are presented in Appendix A.

Optimization of Plan 1

The H_s exceeded 10 percent of the time in the entrance channel for the existing entrance and Plans 1a, 1b, 1c, and 1d is shown in Figure 50. The H_s is about 1.1-1.2 m (3.5-4.0 ft) at the exposed end of the channel, dropping to 0.6 m (2 ft) or less at the protected end of the entrance channel transect. The H_s is nearly constant in the outer entrance channel and then decreases in parts of the channel sheltered by the shallow reef and breakwater extension. The longer the extension, the further seaward H_s drops below the USACE channel criterion.

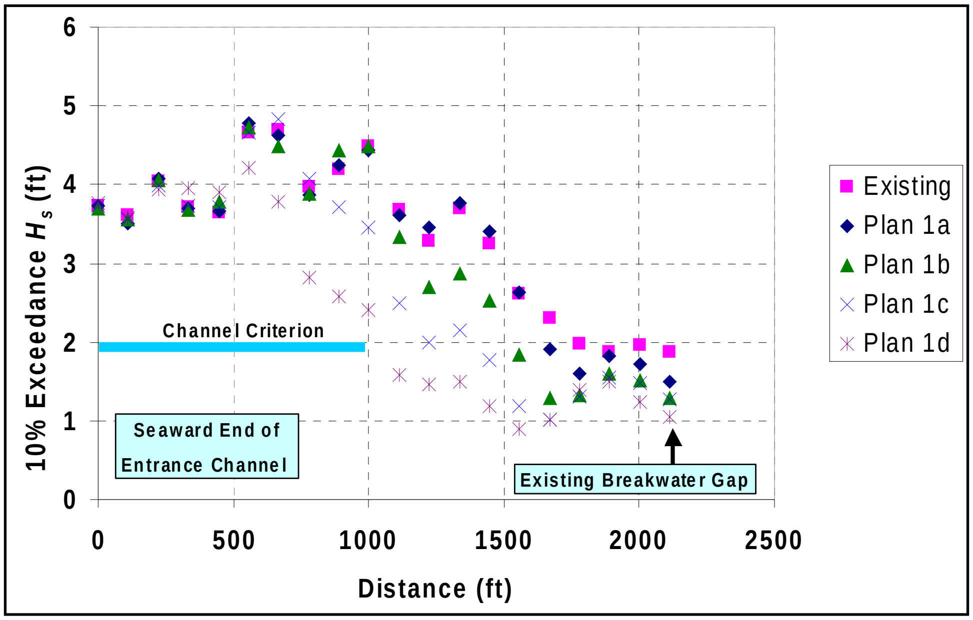

Figure 50. Comparison of H_s exceeded 10 percent of time in entrance channel, existing harbor and Plans 1a, 1b, 1c, and 1d

The effect of the breakwater extension is evident in the middle part of the harbor basin (Figure 51). The H_s in Plan 1a is lower than in the existing harbor throughout the middle basin. The H_s in Plan 1b is consistently lower than in Plan 1a. Plan 1c results are nearly the same as those for Plan 1b, but Plan 1d provides another small reduction of H_s in the basin.

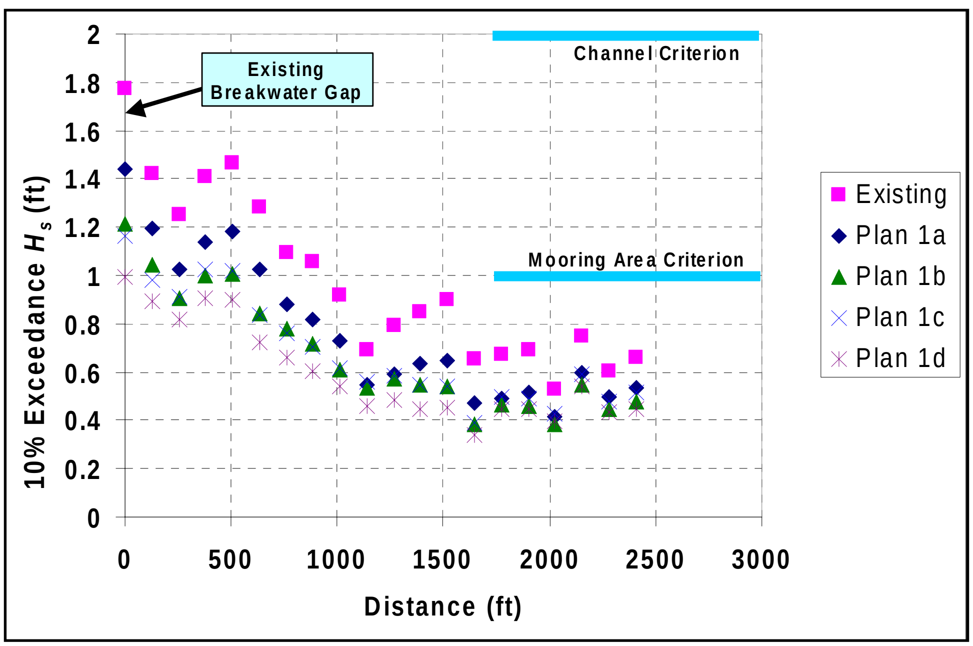

Figure 51. Comparison of H_s exceeded 10 percent of time in harbor mid-basin, existing harbor and Plans 1a, 1b, 1c, and 1d

The difference between the Plan 1 variations is especially evident at the barge pier (Figure 52). For Plan 1a, the average H_s along the pier is reduced from about 0.4 m (1.35 ft) for the existing harbor to (1.1 ft). Plan 1b further reduces H_s to an average of about 0.2 m (0.75 ft). The Plan 1b H_s is below the USACE criterion along the entire pier. Plans 1c and 1d provide further, but smaller, incremental reductions of H_s along the pier.

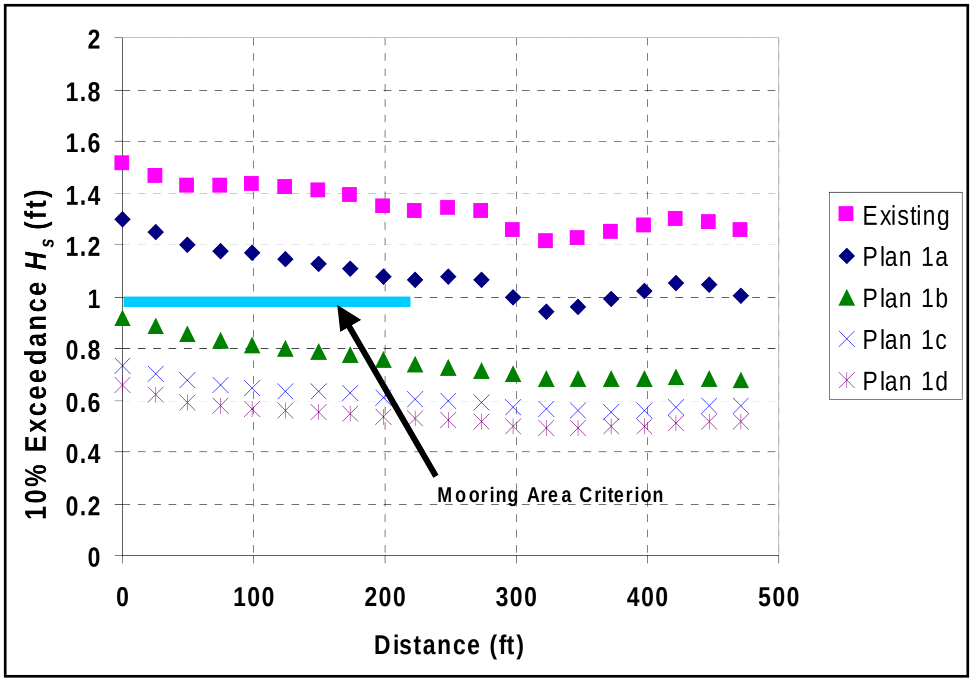

Figure 52. Comparison of H_s exceeded 10 percent of time at barge pier, existing harbor and Plans 1a, 1b, 1c, and 1d

Along the Transpacific Pier, the H_s exceeded 10 percent of the time is significantly reduced in Plan 1a versus the existing condition (Figure 53). Another significant reduction is evidenced in Plan 1b, with relatively small additional gains in Plans 1c and 1d. Plan 1b is the shortest breakwater extension that reduces wave conditions along the entire pier to meet the USACE mooring area criterion.

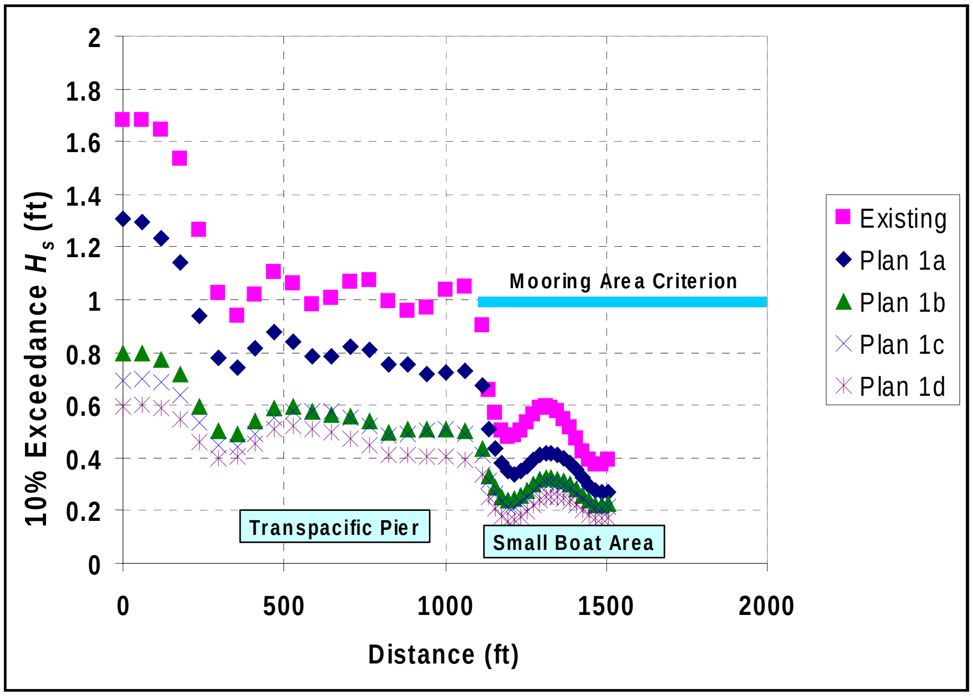

Figure 53. Comparison of H_s exceeded 10 percent of time at Transpacific Pier and small boat area along southeast shore, existing harbor and Plans 1a, 1b, 1c, and 1d

At the south end of the harbor, including the LST dock, H_s exceeded 10 percent of the time is less than the USACE mooring area criterion for the existing harbor and all variations of Plan 1 (Figure 54). Plan 1a provides a small improvement over the existing harbor. Plans 1b, 1c, and 1d provide an additional small improvement over Plan 1a.

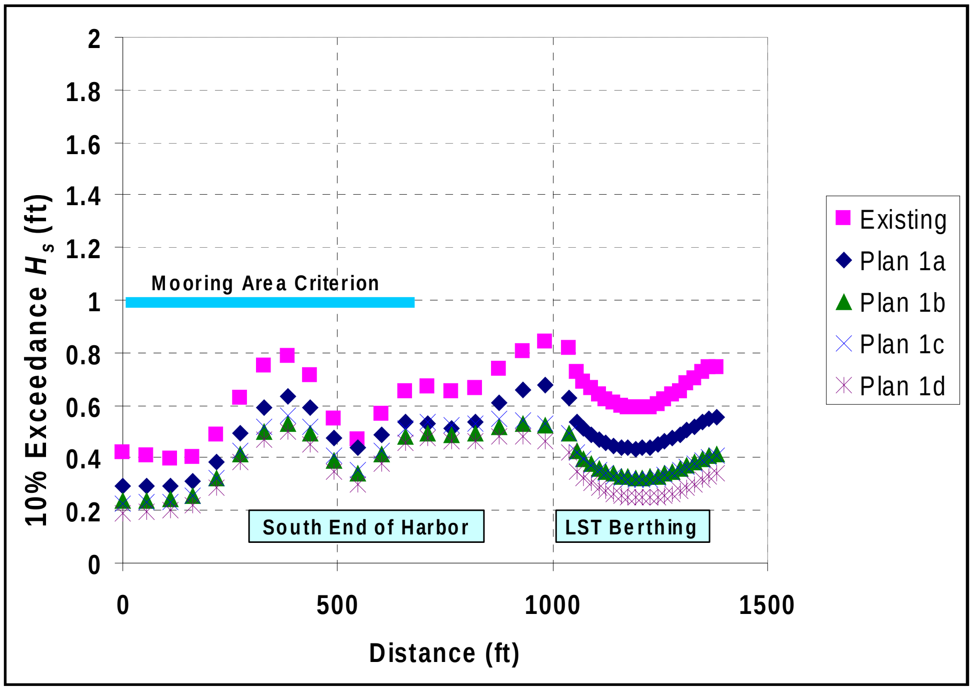

Figure 54. Comparison of H_s exceeded 10 percent of time along south shore of harbor and LST berthing area, existing harbor and Plans 1a, 1b, 1c, and 1d

Overall, Plan 1b appears to be the optimum variation of the Plan 1 alternatives considered. The extra 76-m (250-ft) length of the breakwater extension in Plan 1b versus Plan 1a provides significantly increased wave protection at the two main commercial piers and reduces H_s below the USACE mooring area criterion along the piers. Additional 76-m (250-ft) extensions of the breakwater in Plans 1c and 1d provide only small improvements in wave conditions. Therefore Plan 1b is used in the following section for evaluation against Plans 2-5. The H_s exceeded 1 percent of the time are higher than those for 10 percent exceedance, but follow a similar pattern (Appendix A).

Evaluation of Plans 1-5

The H_s exceeded 10 percent of the time in the entrance channel for the existing harbor and Plans 1b, 2a, 2b, 3, and 4 is shown in Figure 55. The H_s is nearly constant in the outer entrance channel and then is cut in half over a relatively short distance between the outer edge of the shallow reef or breakwater extension and the entrance gap. The rise in H_s at distance 150-300 m (500-1000 ft) into the entrance channel appears to be a model effect resulting from the model boundary being relatively close to the channel. The Plan 1b breakwater extension provides the most effective protection to the entrance channel, because it is best oriented to block the incident wave climate. Plans 2a, 2b, 3, and 4 lead to wave conditions in parts of the landward end of the entrance channel that are as high as or slightly higher than in the existing. The added breakwater stubs in these plans can reflect wave energy back into the channel.

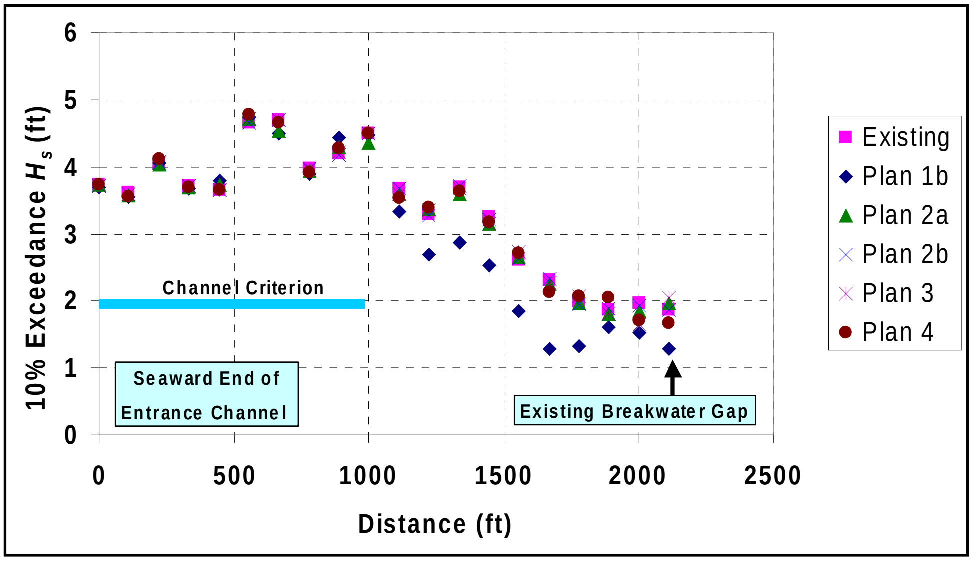

Figure 55. Comparison of H_s exceeded 10 percent of time in entrance channel, existing harbor and Plans 1b, 2a, 2b, 3 and 4

Results for the Plan 5 entrance channel are shown in Figure 56. The Plan 5 transect continues beyond the entrance gap to near the northwest corner of the Transpacific Pier. At this point, far inside the harbor, H_s is reduced to about 0.3 m (1 ft). The H_s exceeded 10 percent of the time in the entrance channel is surprisingly similar between the present and Plan 5 locations.

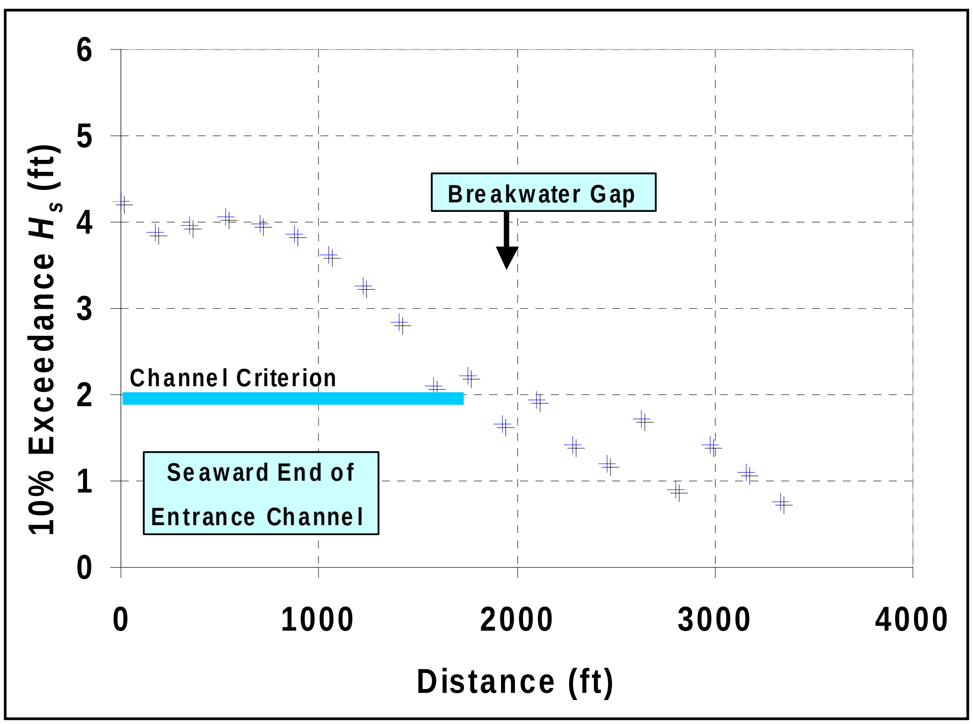

Figure 56. H_s exceeded 10 percent of time in entrance channel, Plan 5

For the existing harbor and Plans 1b, 2a, 2b, 3, and 4, in the middle part of the harbor basin, away from the piers, the H_s exceeded 10 percent of the time is 0.3-0.5 m (1.0-1.5 ft) in the north part of the harbor basin, dropping to 0.2-0.3 m (0.5-1.0 ft) in the south part of the harbor (Figure 57). Plan 5 shows comparable results except in the north part of the basin, where Plan 5 provides excellent protection. The existing harbor and all of the plans provide a mooring area in the south harbor, where small boats are often moored, that satisfies the USACE tranquility criterion.

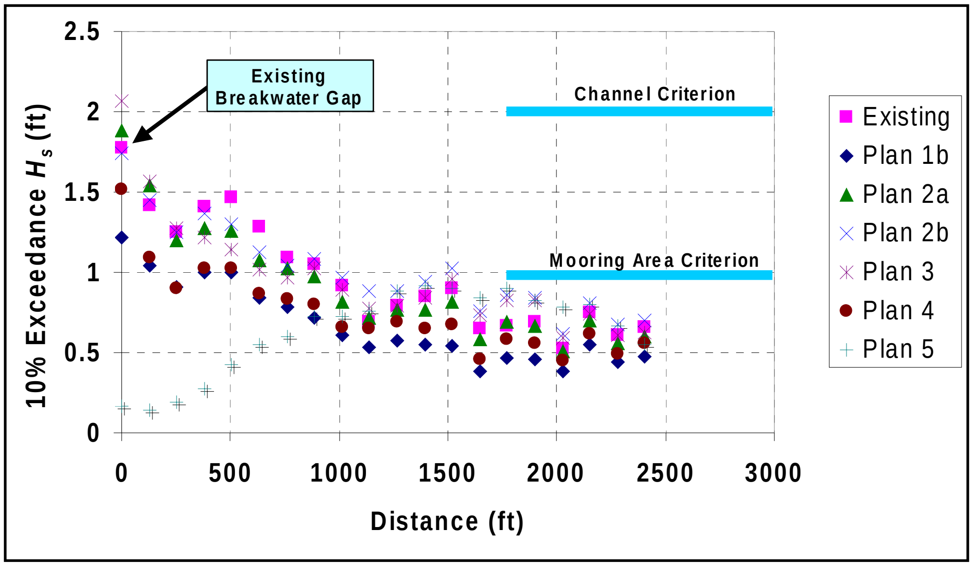

Figure 57. Comparison of H_s exceeded 10 percent of time in harbor mid-basin, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

Along the barge pier, H_s values exceeded 10 percent of the time are greater than 0.3 m (1 ft) for the existing harbor (Figure 58). For Plan 2a, H_s exceeds the 0.3-m (1-ft) criterion along the northwest half of its length and meets or falls slightly below the criterion along its southeast half. Plans 1b, 2b, 3, and 4 consist of breakwater structures that give a more direct sheltering of the barge pier and they result in a considerable reduction in H_s all along the pier. Plans 2b, 3, and 5 provide exceptionally good protection to the northwest part of the pier. In Plan 5, the H_s along the southeast end of the pier, which is the more exposed area for this plan, slightly exceeds the USACE criterion. Overall, Plan 2b provides the best protection for the barge pier, giving H_s exceeded 10 percent of the time of 0.2 m (0.5-0.7 ft), a significant reduction from existing wave conditions along the pier.

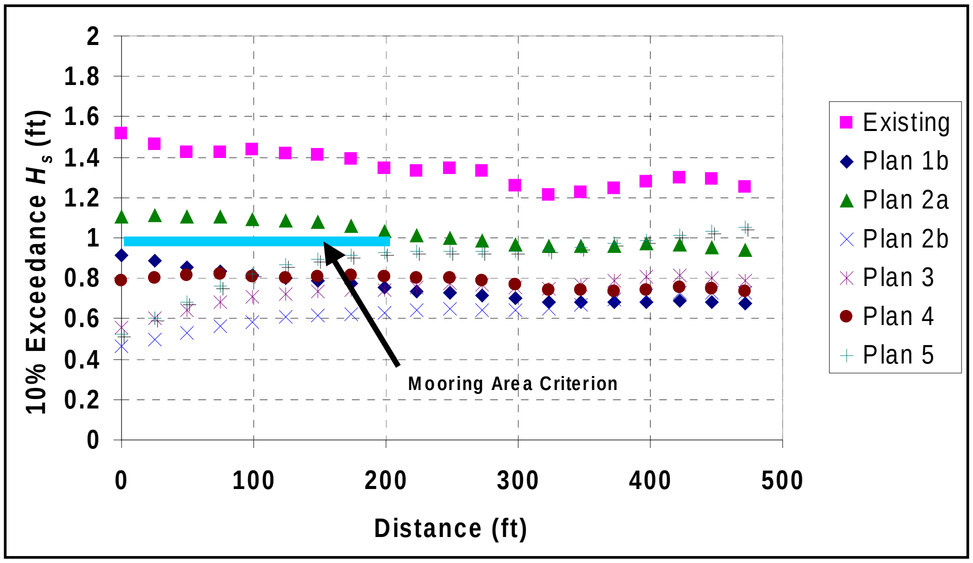

Figure 58. Comparison of H_s exceeded 10 percent of time at barge pier, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

At the Transpacific Pier, differences between plans are not as great as along the barge pier (Figure 59). The plans generally show reduced values of H_s exceeded 10 percent of the time compared with existing conditions, especially at the northwest end of the pier. The exception is Plan 5, which exposes this pier to waves coming through the relocated harbor entrance. The resulting H_s is comparable to existing conditions in the mid part of the pier. Plan 1b is most effective at satisfying the USACE criterion and protecting the Transpacific Pier, giving H_s values along the pier of about 0.2 m (0.5-0.8 ft). Plans 2a, 2b, 3, and 4 also provide an acceptable level of protection.

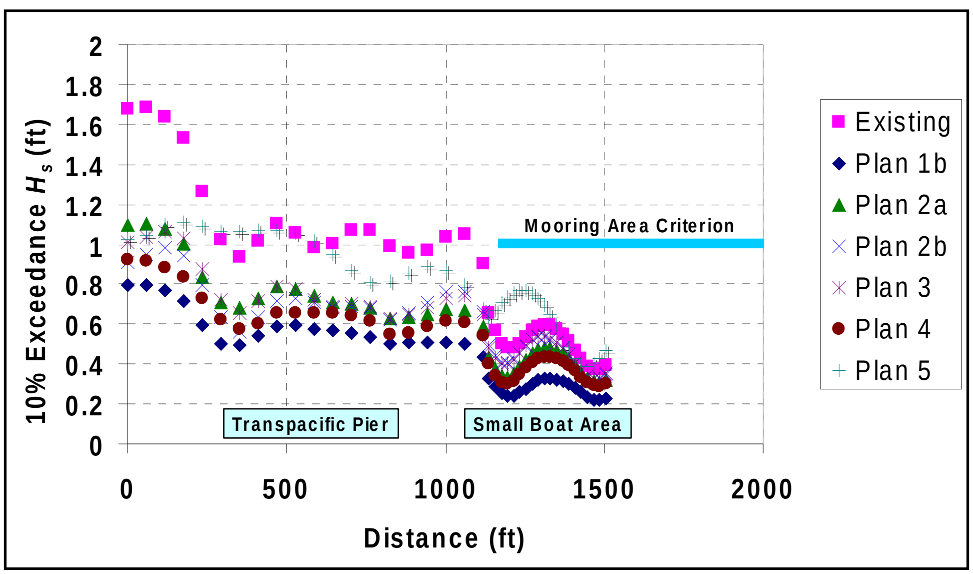

Figure 59. Comparison of H_s exceeded 10 percent of time at Transpacific Pier and small boat area along southeast shore, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

The results for the barge pier can be evaluated in light of the Transpacific Pier existing conditions. The H_s exceeded 10 percent of the time at the existing Transpacific Pier is about 0.3 m (1 ft). Thus, Plan 2a reduces H_s along the barge pier to about the same as existing conditions experienced along the Transpacific Pier. Plans 1b, 2b, 3, and 4 provide more tranquil conditions at the barge pier than at the existing Transpacific Pier. These comparisons may be helpful in using past experience at the Transpacific Pier to predict the operability of the barge pier after a plan harbor modification has been constructed.

At the south end of the harbor basin and along the LST berthing area, the H_s exceeded 10 percent of the time in the plans is generally lower than or equal to that in the existing harbor (Figure 60). The main exceptions are Plans 2b and 5, which show a small increase in H_s at the east end of the LST berthing area and, for Plan 2b, about 120 m (400 ft) further east.

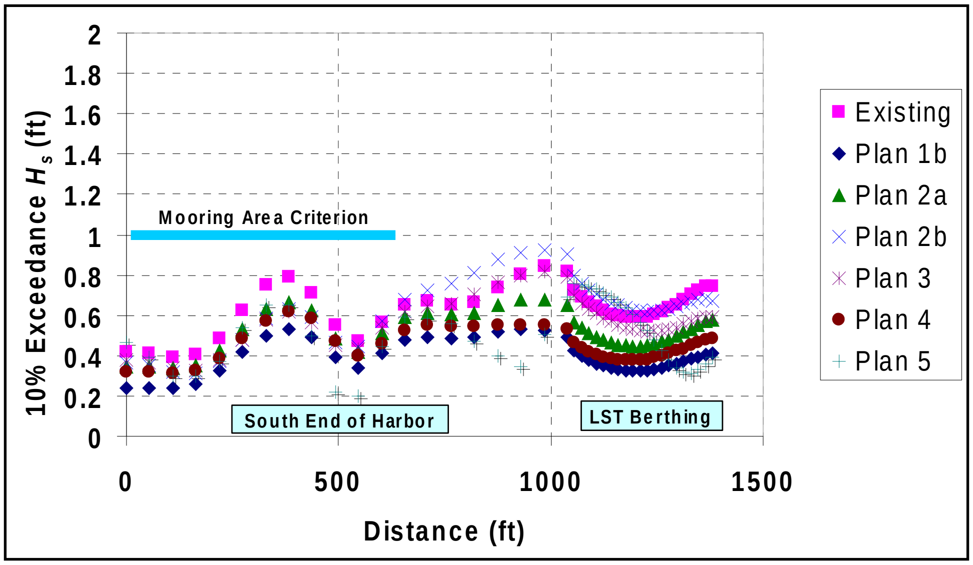

Figure 60. Comparison of H_s exceeded 10 percent of time along south shore of harbor and LST berthing area, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

Another useful basis for comparing harbor alternatives is the number of hours per year during which H_s exceeds various threshold values. For reference, ten percent of the year corresponds to 876 hrs. That information was estimated for the barge and Transpacific piers. The H_s threshold values considered begin at 0.3 m (1 ft) and increase above that in 0.15-m (0.5-ft) increments. For each commercial pier, the average, standard deviation, and maximum number of hours per year exceeding each threshold were computed from the twenty evenly-spaced points along the pier length (Tables 9-15). Since wave period and direction also impact operations at piers, additional information about these parameters at the barge and Transpacific Piers was developed at the request of the U.S. Army Corps of Engineers Institute for Water Resources through POH (Appendix B).

The H_s exceeded 1 percent of the time is shown in Appendix A. Although these H_s values are higher than the H_s exceeded 10 percent of the time, they follow a very similar pattern. The USACE criteria are based on H_s exceeded

10 percent of the time, but the 1 percent exceedance values are also worthy of consideration for a deep draft harbor. The H_s exceeded 1 percent of the time may be experienced for a total of 3-4 days per year. Harbor operations may be vulnerable to the H_s exceeded 1 percent of the time and harbor operations may need to be adjusted to avoid impacts from these wave conditions. For example, the H_s exceeded 1 percent of the time in the plans at the Transpacific Pier is at about the level of the H_s exceeded 10 percent of the time at the existing barge pier. If moored vessels have a difficult time now at the barge pier, they could experience the same conditions at the Transpacific Pier in the plan harbors, but with a greatly reduced frequency of occurrence.

Table 9
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Existing Harbor

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Std. Dev. hr	Maximum hr	Average hr	Std. Dev. hr	Maximum hr
1.0	1086	68	1225	849	238	1323
1.5	561	80	714	388	229	870
2.0	228	45	326	179	142	490
2.5	101	23	143	74	75	241
3.0	43	11	67	29	47	130
3.5	13	11	36	13	25	69
4.0	1	2	8	6	13	35
4.5				1	3	12
5.0						1

Table 10
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Plan 1b

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Std. Dev. hr	Maximum hr	Average hr	Std. Dev. hr	Maximum hr
1.0	373	101	598	188	118	450
1.5	89	36	171	30	42	126
2.0	16	16	53	4	9	27
2.5	1	2	9			

Table 11
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Plan 2a

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Std. Dev. hr	Maximum hr	Average hr	Std. Dev. hr	Maximum hr
1.0	735	73	837	400	217	848
1.5	243	47	305	115	97	331
2.0	78	18	104	29	44	124
2.5	25	11	39	8	16	48
3.0	2	2	6	1	2	6

Table 12
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Plan 2b

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Std. Dev. hr	Maximum hr	Average hr	Std. Dev. hr	Maximum hr
1.0	211	78	343	359	153	676
1.5	46	29	96	96	59	222
2.0	3	5	14	22	29	90
2.5				4	8	26

Table 13
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Plan 3

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Std. Dev. hr	Maximum hr	Average hr	Std. Dev. hr	Maximum hr
1.0	333	96	461	406	189	788
1.5	83	32	125	118	81	294
2.0	15	11	31	30	40	119
2.5				8	15	45
3.0				1	2	5

Table 14
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Plan 4

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	**Std. Dev. Hr**	**Maximum hr**	**Average hr**	**Std. Dev. hr**	**Maximum hr**
1.0	386	44	436	284	142	581
1.5	101	20	126	64	63	201
2.0	13	8	22	10	19	51
2.5				1	2	5

Table 15
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, Plan 5

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	**Std. Dev. hr**	**Maximum hr**	**Average hr**	**Std. Dev. hr**	**Maximum hr**
1.0	534	197	796	652	201	886
1.5	125	65	250	175	84	291
2.0	30	18	62	47	27	88
2.5	5	5	18	8	7	19
3.0					1	2
3.5						1

5 Harbor Oscillations

To evaluate harbor resonance characteristics, the CGWAVE numerical model was run for the existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5. Incident long wave periods ranged from 25 sec to 1,000 sec in very fine increments, as discussed in Chapter 3. These evaluations were included because oscillations may be an important part of interpreting the existing harbor wave response, and modifications to the harbor can potentially lead to increased operational problems due to harbor oscillations. Amplification factor results are presented in the following section. Discussion of the results relative to operational performance criteria is given in the final section of this chapter.

Amplification Factors

Background

Amplification factors for the long waves involved in harbor oscillation behave differently than those for wind waves and swell. Long waves, because of their length relative to harbor dimensions and their reflectivity from harbor boundaries, form standing wave patterns in the harbor. Standing wave behavior in a simple closed basin of uniform depth is illustrated in Figure 61. In the fundamental mode of oscillation, antinodes occur at both basin walls and a node midway between walls. The distance between walls is equal to one-half of the oscillation wavelength. Second and third modes of oscillation are also illustrated. Antinodes always occur at the walls. Additional antinodes and nodes occur at regular intervals between walls, with the number of antinodes and nodes dependent on the mode of oscillation.

The water surface in a standing wave has its greatest vertical motion at antinodes. There is no vertical movement at an ideal node, but horizontal velocities reach a maximum there. In terms of amplification factors, long waves, $A_{amp,l}$, this behavior gives large values of $A_{amp,l}$ at antinodes and small values around nodes. Contrary to wind waves and swell, small values of $A_{amp,l}$ are not necessarily indicative of a tranquil harbor area.

Phases in a standing wave also behave differently than phases for typical wind waves and swell. For example, the water surface in the fundamental mode of oscillation in Figure 61 simultaneously reaches a maximum at every point to the left of the node. These points are all in phase. At the same time, every point to the right of the node reaches a minimum value. These points are also in phase with each other but exactly out of phase with the points to the left of the node. Thus phases in a simple standing wave are constant between an antinode and node. They quickly change by 180 deg (or π radians) across the node and remain constant up to the next node or boundary.

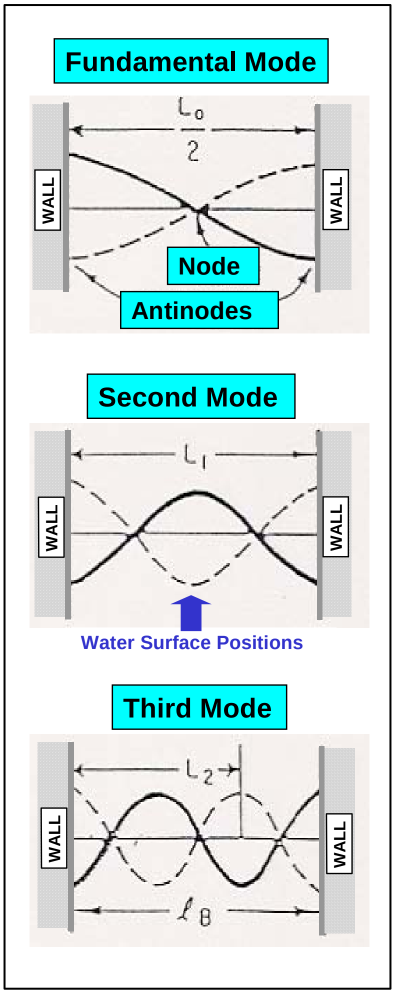

Figure 61. Harbor oscillation definitions

Existing harbor

Amplification factors for pier areas in the existing harbor are shown as a function of wave frequency in Figure 62. Amplification factor shown at each frequency and pier location is the maximum value for the three output points along the length of the pier. Similarly for the LST landing area, results represent the higher value for the two output points in the area.

Some frequencies produce a strong resonant amplification, with peak $A_{amp,l}$ values between about 3 and 14. Many of the same resonant frequencies appear at all pier areas, though the strength of amplification can vary considerably. The dominating peak for the small boat basin around 0.008 Hz (125 sec) indicates that area may be strongly impacted by long period resonance in the existing harbor. A large peak at very low frequency (0.0016 Hz or 625-sec period) shows at every location and plan. This peak represents the Helmholtz (or grave) mode of oscillation, in which the entire harbor rises and falls in unison. Phase is constant over the whole harbor.

Amplification factor and phase contour plots for three prominent resonant peaks at frequencies lower than 0.02 Hz (50-sec period), excluding Helmholtz resonance, show oscillation patterns in the existing harbor (Figure 63). These peaks are numbered in Figure 62 for easy reference. In amplification factor plots, areas of high amplification are evident as orange and red colors. Corresponding phase contours are also shown in the figure. Areas in which $A_{amp,l}$ is near zero and phase contours are tightly bunched indicate nodal zones. Relatively strong currents would occur across nodal lines during resonance events. The phase plots also indicate areas of the harbor that rise and fall together during the resonant condition (areas with the same color). Thus the oscillation patterns can be interpreted. Nodes that may impact present harbor operations intersect the Transpacific Pier for 130.5-sec resonance and the southeast ends of both the barge and Transpacific piers for 59.9-sec resonance.

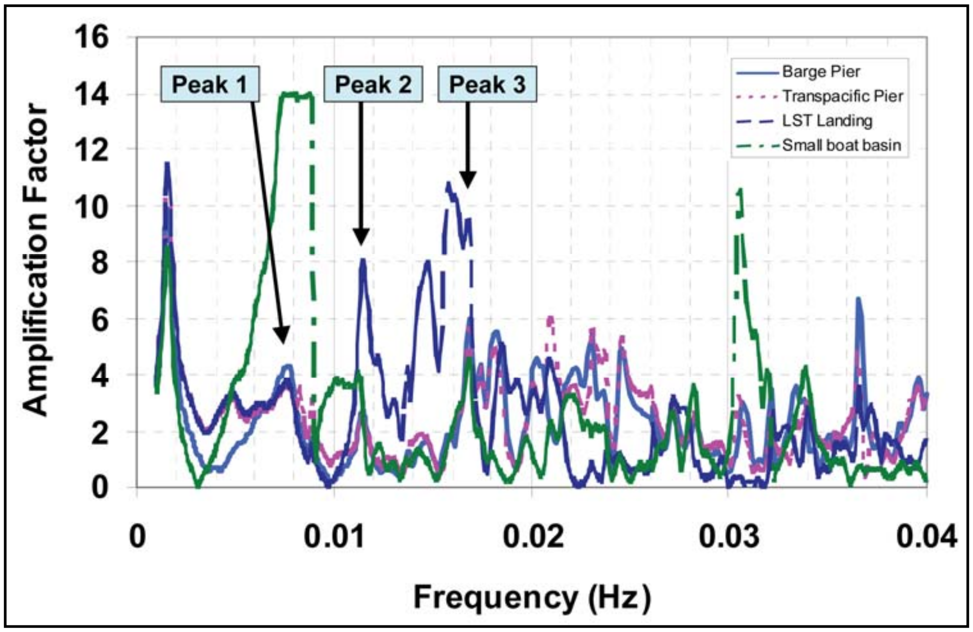

Figure 62. Long wave response, existing harbor

The 130.5-sec resonance (peak 1) is a simple rocking between the northwest and southeast ends of the harbor. The 87.0-sec resonance (peak 2) is a rocking between the southwest and southeast corners of the harbor and the area between the barge pier and exposed end of the Transpacific Pier. The 59.9-sec resonance (peak 3) is a more complex pattern. It represents a higher order mode of oscillation between harbor areas, similar to those in Figure 61 but adapted to the shape of Kawaihae Harbor. It indicates nodal areas intersecting the southeast end of both the barge and Transpacific piers.

Long wave amplification factors shown here may be overestimated for resonant peaks at periods less than about 100 sec (0.01-Hz frequency). Wave reflection coefficient at all solid boundaries was set to 1.0 for all long wave runs, but comparison of model results to field data in a previous study showed that peaks at the shorter long wave periods tend to be overestimated (Thompson et al. 1996). Some reduction in reflection coefficient as wave period decreases could be expected physically. In the previous study, it was demonstrated that even a small decrease in reflection coefficient to $K_r = 0.95$ can reduce resonant peaks dramatically.

Plan 2b

Plan 2b is an alternative with potential for harbor oscillation concerns. The plan includes a new breakwater stub adjacent to the exposed end of the barge pier. While the stub provides good protection from wind waves and swell, harbor oscillations will tend to reflect in the corner created by the stub and land, and these will have at least a localized impact on the barge pier. Thus, Plan 2b is used to illustrate changes in harbor oscillation characteristics relative to the existing harbor. Results for the other plans are given in the following subsection.

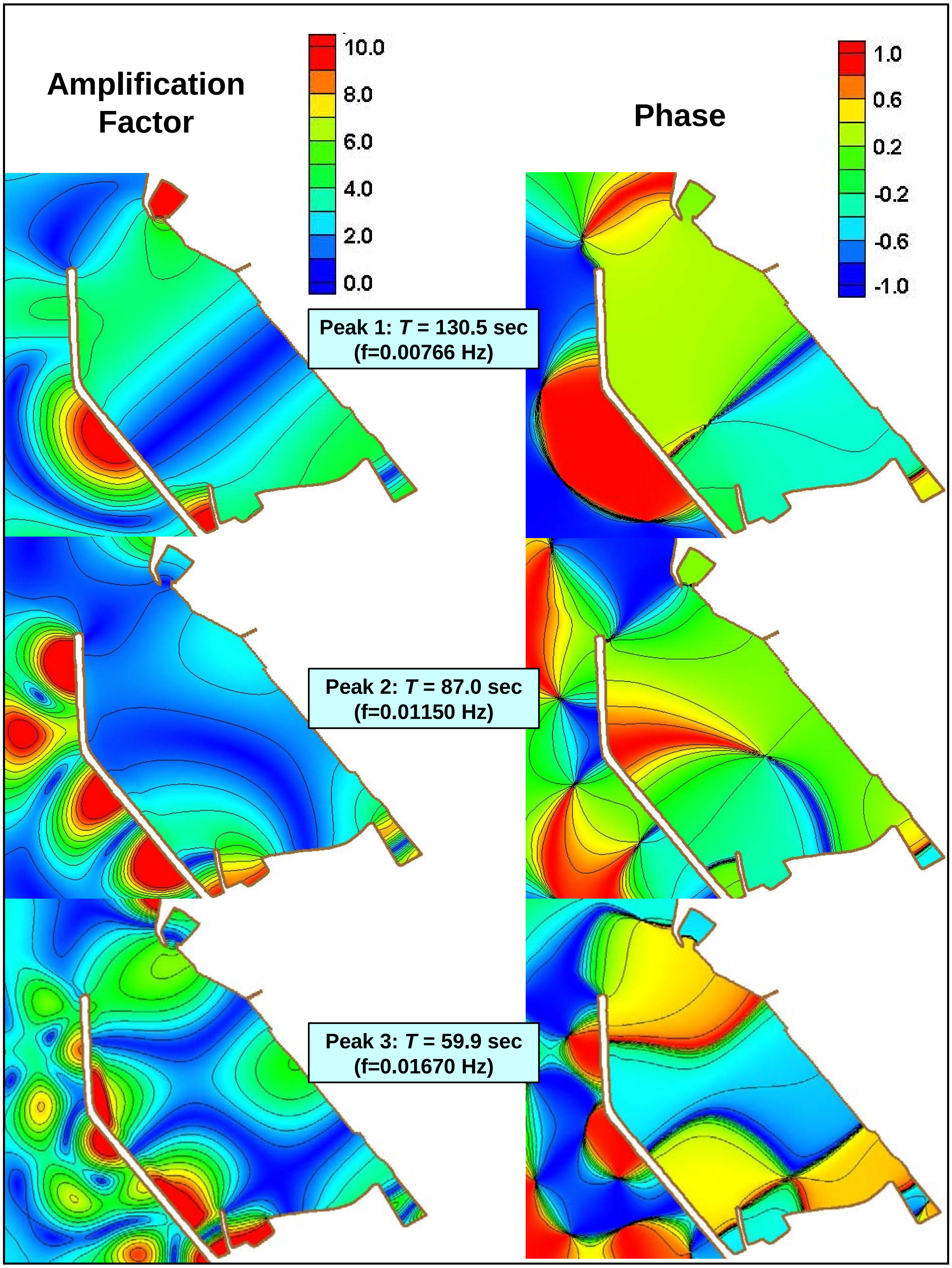

Figure 63. Resonant long wave amplification factor and phase contours, existing harbor

Amplification factors for main pier areas in Plan 2b show a presence of resonant peaks that resembles those for the existing harbor (Figure 64). Even the strength of resonance is about the same for many of the peaks, especially the peaks at lower frequencies, indicating that the small breakwater stub in Plan 2b has little effect on the longer period resonances. As with the existing harbor, amplification factors shown are maximum values along the length of each pier. Since the low frequency resonances are so similar between existing and Plan 2b harbors, peaks for detailed display in Plan 2b were chosen at somewhat higher frequencies because they show stronger amplification than the existing harbor at commercial piers. Amplification factor and phase over the harbor for peak 1 shows a pattern very similar to peak 3 for the existing harbor (Figure 65). Resonant period is 2.8 seconds shorter than for the existing harbor because of additional deepening in Plan 2b. Patterns for peaks 2 and 3 show that the corner formed by the plan breakwater stub becomes an antinode for higher order resonant modes between the stub and the southeast end of the harbor. These resonances occur across the commercial pier areas. Nodes that may impact harbor operations intersect the Transpacific Pier in the peak 2 pattern and both commercial piers in the peak 3 pattern.

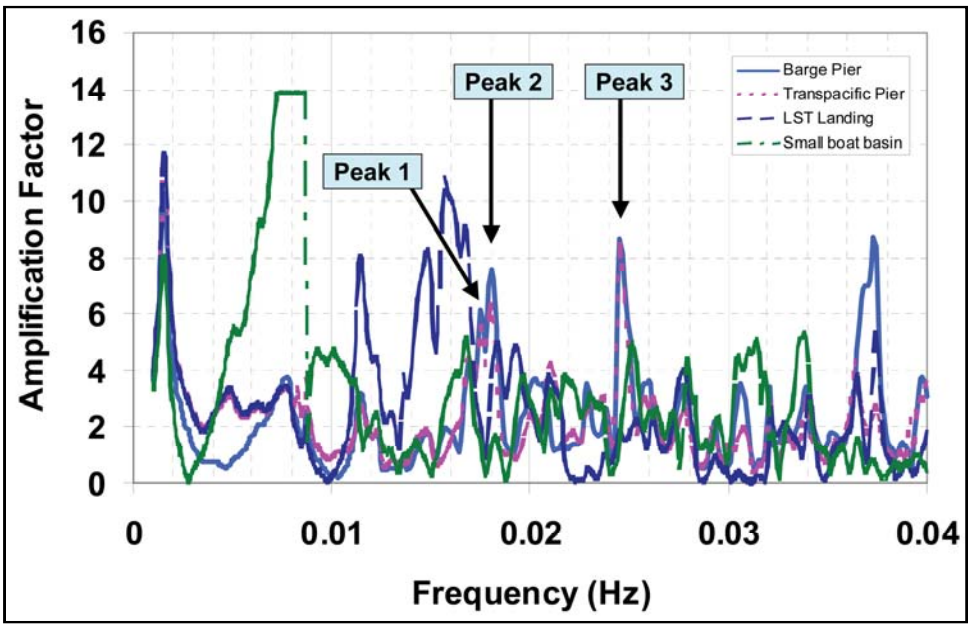

Figure 64. Long wave response, Plan 2b

Plans 1b, 2a, 3, 4, and 5

Amplification factors for main pier areas in Plans 1b, 2a, 3, 4, and 5 are given in Figures 66-70. As with the existing harbor and Plan 2b, amplification factors shown are maximum values along the length of each pier. The most notable difference between these plans and the existing harbor is for Plan 2a, which shows high amplification factors at 0.0016 Hz (625-sec period) and very high amplification factors at the LST landing at 0.012-0.018 Hz (56-83-sec period). The significance of these results for harbor operations is discussed in the following section.

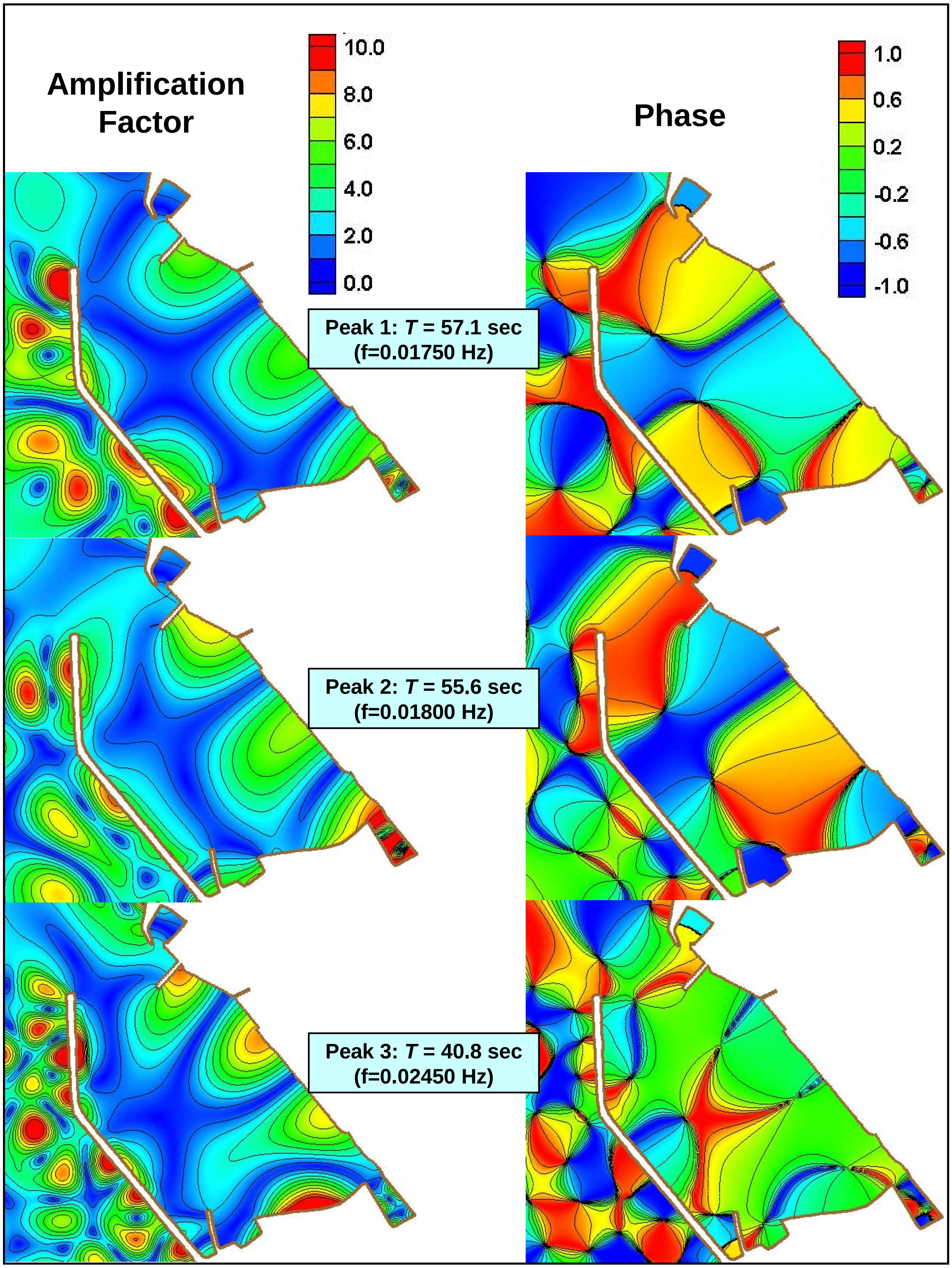

Figure 65. Resonant long wave amplification factor and phase contours, Plan 2b

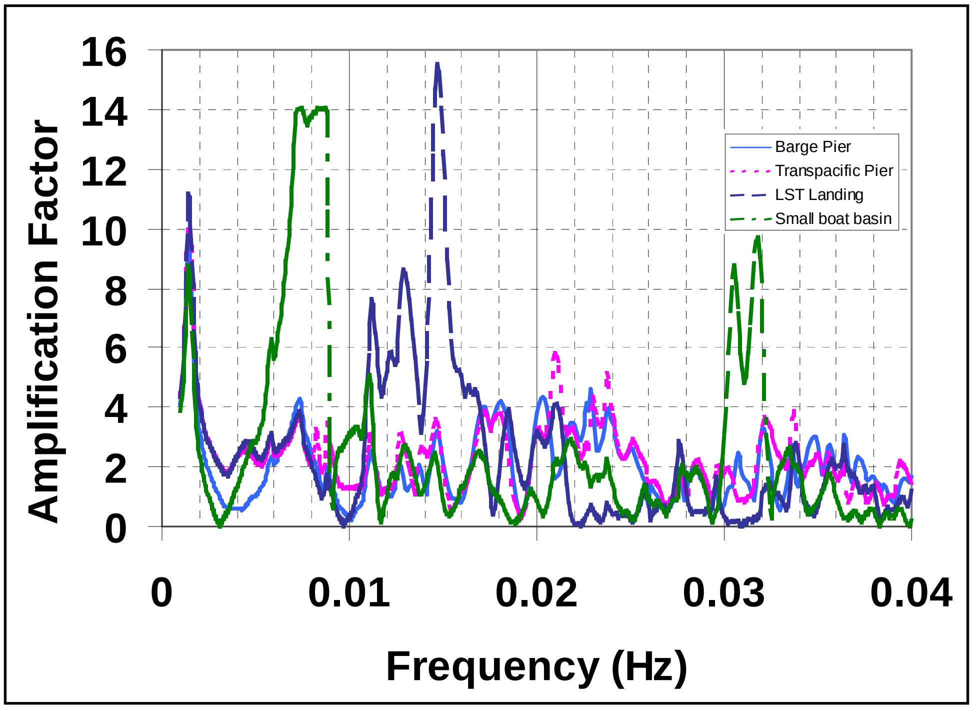

Figure 66. Long wave response, Plan 1b

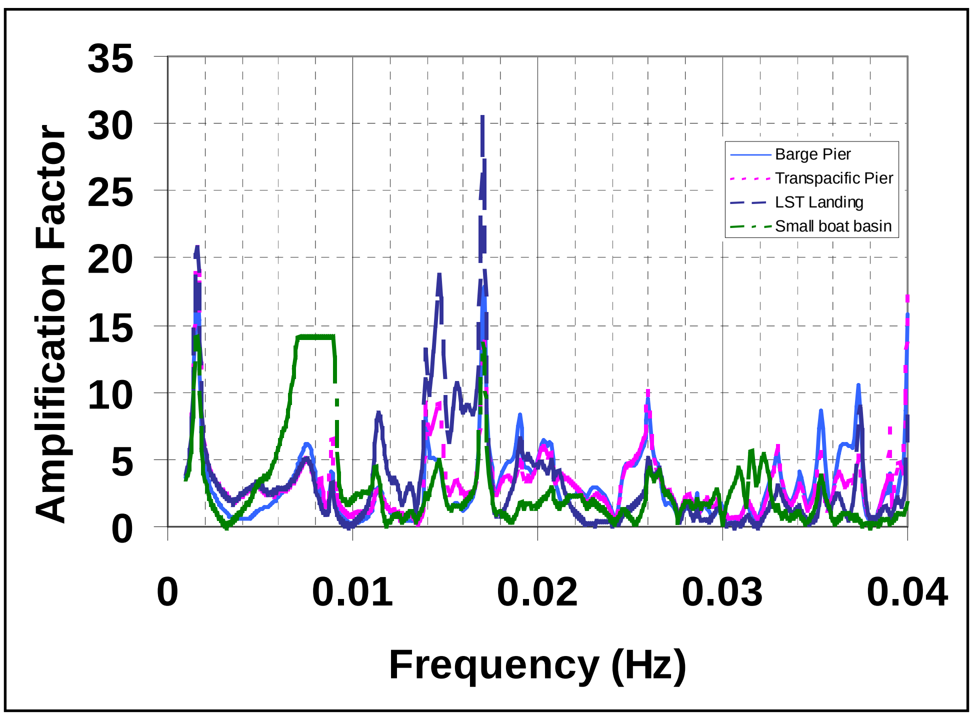

Figure 67. Long wave response, Plan 2a

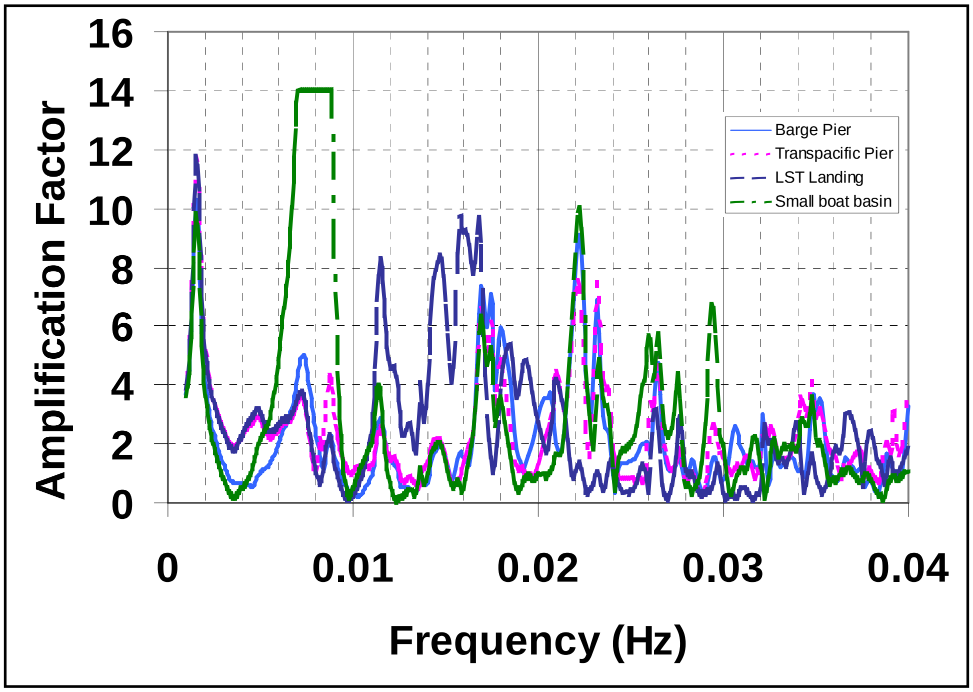

Figure 68. Long wave response, Plan 3

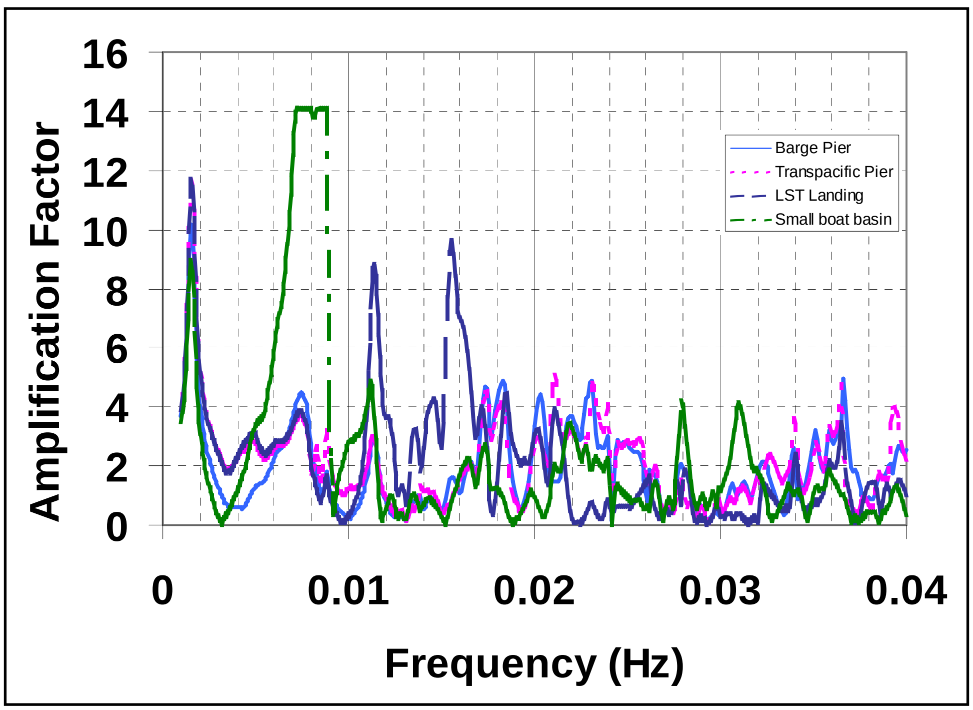

Figure 69. Long wave response, Plan 4

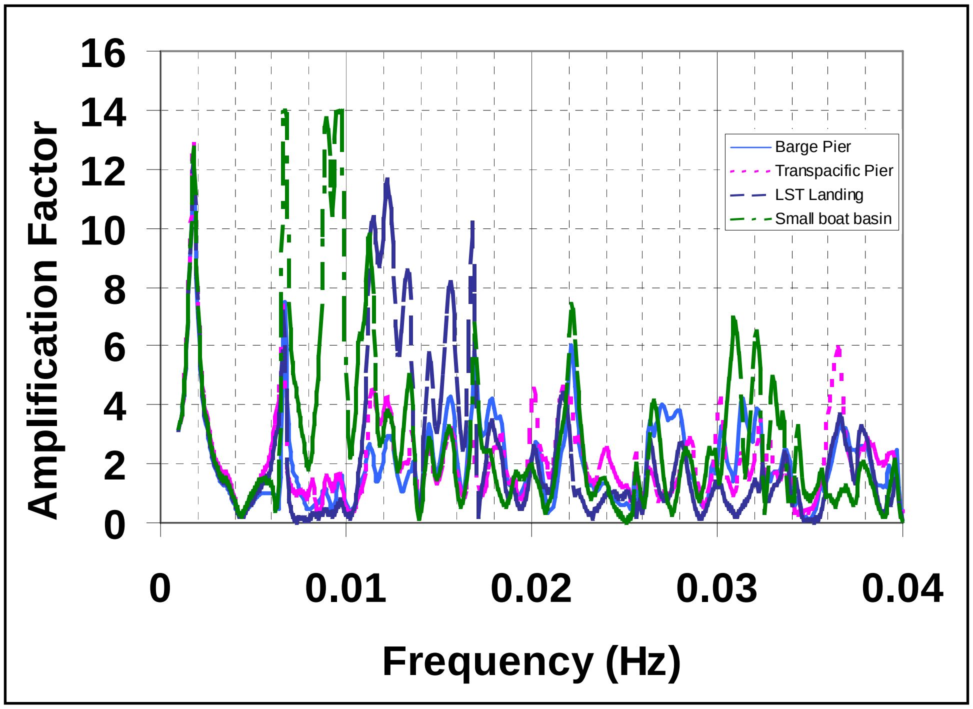

Figure 70. Long wave response, Plan 5

Evaluation against Operational Criteria for Long Waves

Procedures for evaluating the operational acceptability of different harbor plans subjected to long waves were reviewed by Thompson et al (1996), Thompson, Boc, and Nunes (1998), and PIANC (1995). The operational guideline applied in this study is based on the value of $A_{amp,l}$ for the higher resonant peaks. Experience with Los Angeles and Long Beach Harbors has indicated that if $A_{amp,l}$ is greater than approximately 5, some operational difficulties may be encountered. If $A_{amp,l}$ is greater than 10, major operational problems can be expected (Personal Communication, 1996, William Seabergh, Research Hydraulic Engineer, CHL, ERDC).

This guideline may be applied to the plots of $A_{amp,l}$ versus frequency. If the very low frequency Helmholtz peak and frequencies greater than 0.01 Hz (wave periods shorter than 100 sec, for which K_r would be less than 1.0) are excluded, the existing harbor has maximum $A_{amp,l}$ values of approximately 4 at the commercial pier and LST landing areas. Similarly, Plans 1b, 2b, 3, and 4 appear to be acceptable, with amplification factors less than 5 over this frequency range. Based on this metric, the existing harbor and Plans 1b, 2b, 3, and 4 appear to be free of operational difficulties due to long waves. Plans 2a and 5, which have peak amplification factors in the range 5-8 at commercial piers and LST landing, may create some operational concerns.

Long wave frequencies higher than 0.01 Hz should also be considered, though harbor response is somewhat exaggerated due to the use of completely reflecting boundaries in modeling. In frequency range 0.01-0.03 Hz (33-100 sec period), the existing harbor has maximum $A_{amp,l}$ of 6 at the commercial piers and 10-11 at the LST landing. At the commercial piers, Plans 1b, 4, and 5 have $A_{amp,l}$ less than 6, while Plans 2a, 2b, and 3 show some increased $A_{amp,l}$ relative to the existing harbor. At the LST landing, Plans 2b, 3, 4, and 5 have maximum $A_{amp,l}$ generally similar to the existing harbor, while Plans 1b and 2a show increased peak values.

Overall, Plan 4 performed best relative to harbor oscillation concerns. Plan 2a performed poorly and it is not recommended for further consideration. The other plans showed mixed results. Plan 5 shows potentially troublesome oscillations at 0.0067 Hz (149-sec period), judged to be a significant issue. Plans 1b, 2b, and 3 raised concerns about oscillations at frequencies above 0.01 Hz (periods shorter than 100 sec), but they may not significantly impact harbor operations. Plan 1b performs very well except for a high $A_{amp,l}$ peak at 0.0147 Hz (68-sec period) at the LST landing. Although this peak is nearly 50 percent higher than in the existing harbor, operational experience with the existing LST landing may provide some judgement about the level of concern. In summary, based on experience with other harbor studies, Plans 1b, 2b, 3, and 4 are expected to be acceptable relative to harbor oscillation concerns.

6 Conclusions and Recommendations

Studies of the wave response of Kawaihae Deep Draft Harbor have produced information about the existing harbor and possible modifications to the harbor. The main results are: a) an improved estimate of wave climate incident to the harbor, and b) an evaluation of wave conditions in the harbor plans and implications for harbor operations.

Wave climate in the vicinity of Kawaihae Deep Draft Harbor was estimated by transforming and combining information from NDBC directional buoys 51026 and 51027 to the study area. The wave model STWAVE was used to determine transformation patterns and relationships. Both island-scale and detailed local STWAVE grids were applied.

The numerical model CGWAVE was used to simulate harbor response to waves. In wind wave and swell screening runs, the model was used to evaluate sensitivity of harbor response to project depth, including existing entrance and harbor depths and plan depths. The harbor wind wave and swell response was not significantly affected by project depth in the range tested. In production runs with full wave climate and four variations of Plan 1, the 305 m (1000 ft) breakwater extension (Plan 1b) was determined to be an initial optimized length. In additional wind wave and swell production runs, the behavior of the existing harbor, Plan 1b, and five alternative modifications to the harbor was evaluated. Model results are compared with criteria for operational acceptability and with experience in the existing harbor to the extent possible.

Wave gauge data collected by POH during January to March 2004 concurrently with this study added significantly to the level of confidence in model results. Directional gauges at the outer end of Kawaihae Deep Draft Harbor entrance channel provided very valuable validation of the island-scale STWAVE modeling. These data coupled with nondirectional gauge data collected in the harbor were the basis for calibration and validation of local CGWAVE modeling.

Uncertainties related to wind wave and swell calculations in the harbor can be addressed as follows:

- The offshore wave climate is derived using directional data from NDBC buoys 51026 and 51027 during the one available year of concurrent measurement. Although an uncertainty is associated with each buoy observation, the measurement bias is generally small. Thus, a year of data can be considered an accurate estimate of the year's wave climate for purposes of this study.

- Wave climate can vary from year to year. Generally, three or more years of data are preferred for estimating non-extreme wave climate information. Multiple years of data from NDBC buoy 51026 indicate that the year was typical for Kawaihae exposures to the west, northwest, and north. Ten years of WIS hindcasts indicate that the year was generally typical for Kawaihae exposures to the southwest. WIS and very limited gauge data collected as part of this study outside Kawaihae Deep Draft Harbor entrance suggest that storm waves from the southwest, occurring about 0.3 percent of the time in the 10-yr WIS hindcast, may be underrepresented in the one-year climate available from buoy 51027. Although this frequency of occurrence is less than normally considered for harbor operation concerns, the possibility of such storms should be considered in evaluating harbor alternatives especially sensitive to high waves from southwest, as with Plan 5.

- Comparison of gauge data summaries collected outside Kawaihae Harbor during Jan-Mar 2004 with information from the same time period in the 1995 wave climate transformed to the gauge location gives an indication of uncertainties in the one-year buoy/model wave climate. Although quantitative comparisons for such small samples from different years are of limited use, the model appears to be generally consistent with data to within one summary band of each parameter. Bandwidths for wave height, period, and direction are 0.3 m (1ft), 2 sec, and 10°, respectively.

- Validation of the CGWAVE model to gauge data collected inside the harbor indicates an uncertainty of about plus or minus 10 percent introduced in the CGWAVE transformation modeling.

The effectiveness of proposed new harbor structures for wind wave and swell protection often has little relationship to protection from long-period oscillations. These two aspects of pier operability are both considered in judging success of the alternative plans.

An overview of performance of the alternative plans is given by their success relative to a simple, meaningful criterion. For wind waves and swell, success was defined as having H_s> 0.3 m (1 ft) less than 10 percent of the time along all commercial piers. The 10 percent level was chosen because the existing Transpacific Pier (which is considered successful for present operations) meets this criterion along most of its length, but the barge pier (which has undue operational limitations due to high wave conditions) exceeds the criterion by 20-50 percent along its length. A previous study concluded that the more limiting criterion H_s> 0.3 m (1 ft) less than 1 percent of the time was more applicable to the commercial pier areas in Kahului Harbor, but that criterion appears to be overly conservative for present operations in Kawaihae Deep Draft Harbor.

For wind waves and swell along the barge pier, Plans 1b, 2b, 3, 4, and 5 were considered successful in providing protection. Plan 2b, which provided the best protection along most of the pier, reduced H_s values exceeded 10 percent of the time to about one-half the present level. The other successful plans provided nearly as much protection as Plan 2b along the more sheltered parts of the pier. For Plan 5, it is noted that rare storms can generate high waves approaching from the southwest, directly in line with the entrance channel.

For wind waves and swell along the Transpacific Pier, Plans 1b, 2b, and 4 were successful in protecting the pier along all of its length. These plans reduced H_s values exceeded 10 percent of the time to about 50-70 percent of the present level. Plan 4 has the potential disadvantage of reflecting incident wave energy from the new breakwater stub directly back into the entrance channel. For the rubble structure modeled, reflected energy was not an apparent problem.

Harbor oscillations characteristics were evaluated for the existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5. Plan 4 showed no indication of harbor oscillation problems. Plans 1b, 2b, and 3 have potential for amplifying higher order resonant modes with periods in the range 35-70 sec, which may be in a sensitive range for moored vessels in the harbor. However, based on past studies, it is expected that these resonances will not be an operational concern. Overall, harbor oscillations are not expected to be a problem for commercial piers in the existing harbor and Plans 1b, 2b, 3, and 4. Oscillations are a potential problem in Plans 2a and 5.

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Appendix A
Results for H_s Exceeded 1 Percent of the Time

This appendix contains results for H_s exceeded 1 percent of the time, similar to figures in the main report for H_s exceeded 10 percent of the time. Figures A1-A5 compare the existing harbor and the four variations of Plan 1. Figures A6-A11 compare the existing harbor, the optimum variation of Plan 1 (Plan 1b), and the other plans modeled (Plans 2a, 2b, 3, 4, and 5).

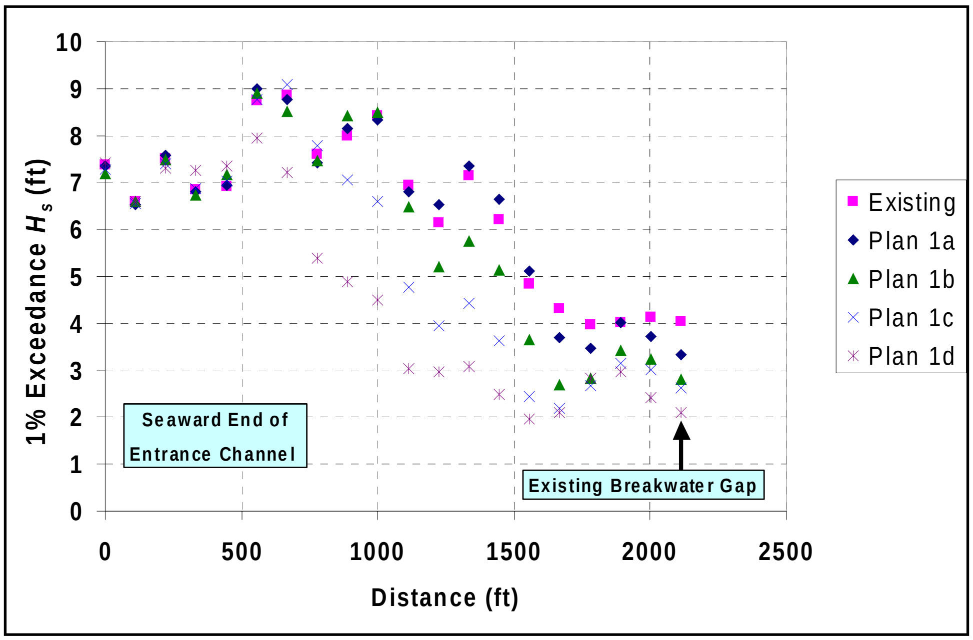

Figure A1. Comparison of Hs exceeded 1 percent of time in entrance channel, existing harbor and Plans 1a, 1b, 1c, and 1d

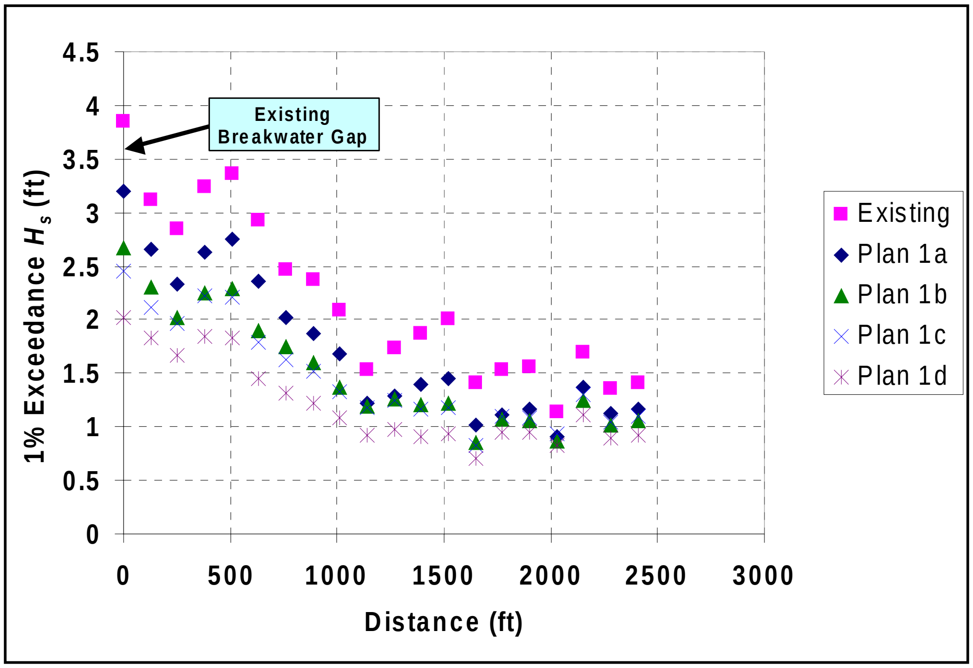

Figure A2. Comparison of H_s exceeded 1 percent of time in harbor mid-basin, existing harbor and Plans 1a, 1b, 1c, and 1d

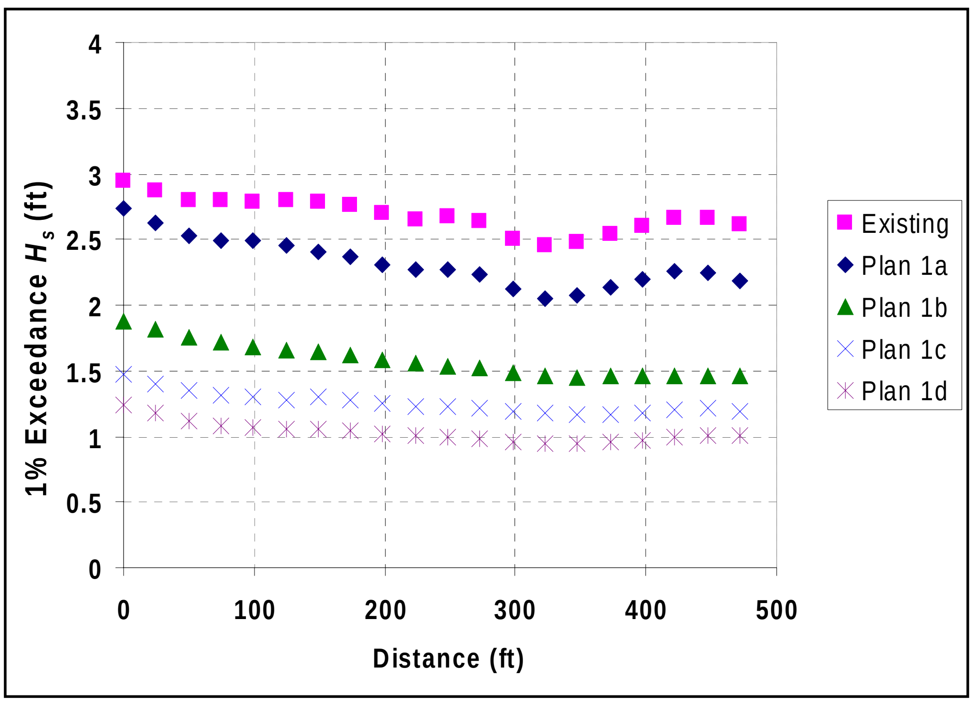

Figure A3. Comparison of H_s exceeded 1 percent of time at barge pier, existing harbor and Plans 1a, 1b, 1c, and 1d

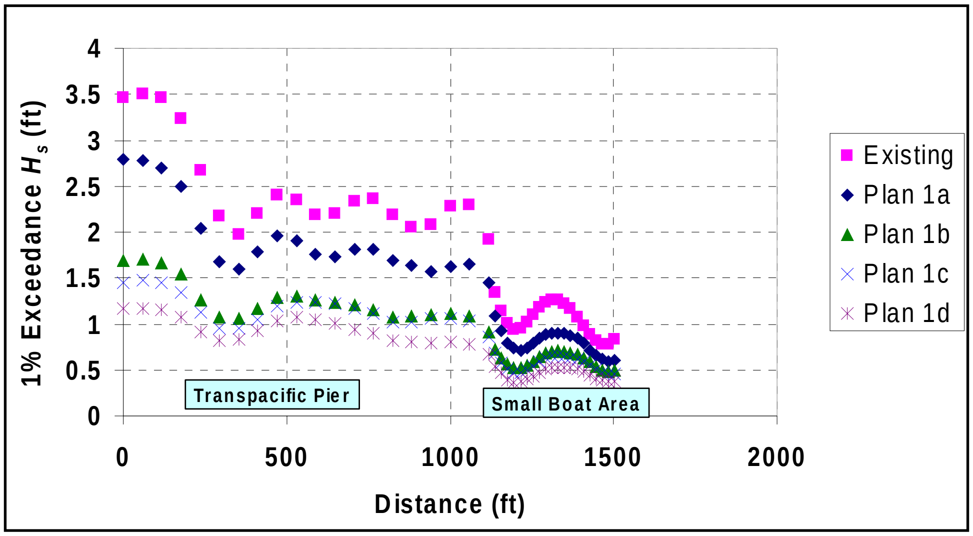

Figure A4. Comparison of H_s exceeded 1 percent of time at Transpacific Pier and small boat area along southeast shore, existing harbor and Plans 1a, 1b, 1c, and 1d

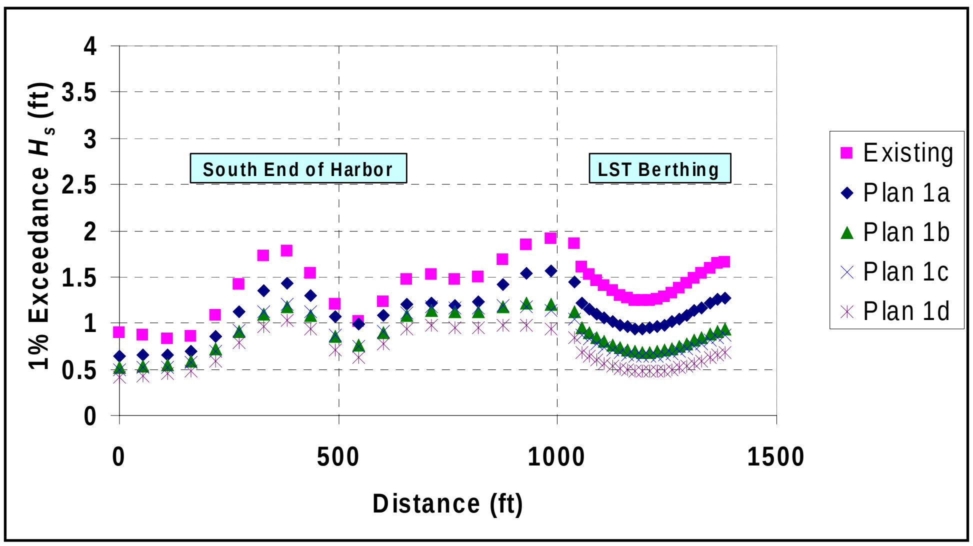

Figure A5. Comparison of H_s exceeded 1 percent of time along south shore of harbor and LST berthing area, existing harbor and Plans 1a, 1b, 1c, and 1d

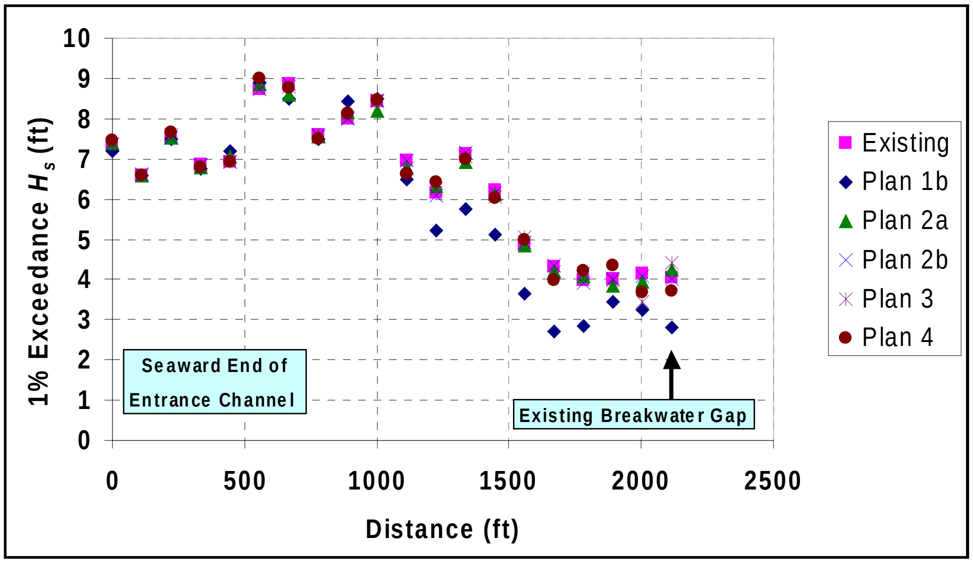

Figure A6. Comparison of H_s exceeded 1 percent of time in entrance channel, existing harbor and Plans 1b, 2a, 2b, 3, and 4

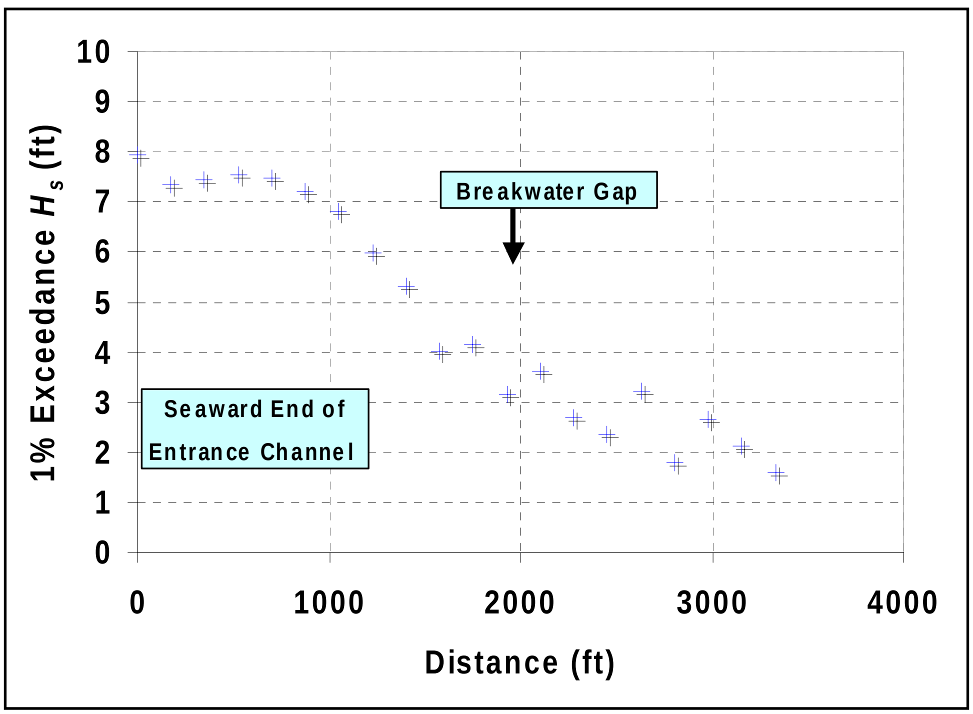

Figure A7. Comparison of H_s exceeded 1 percent of time in entrance channel, Plan 5

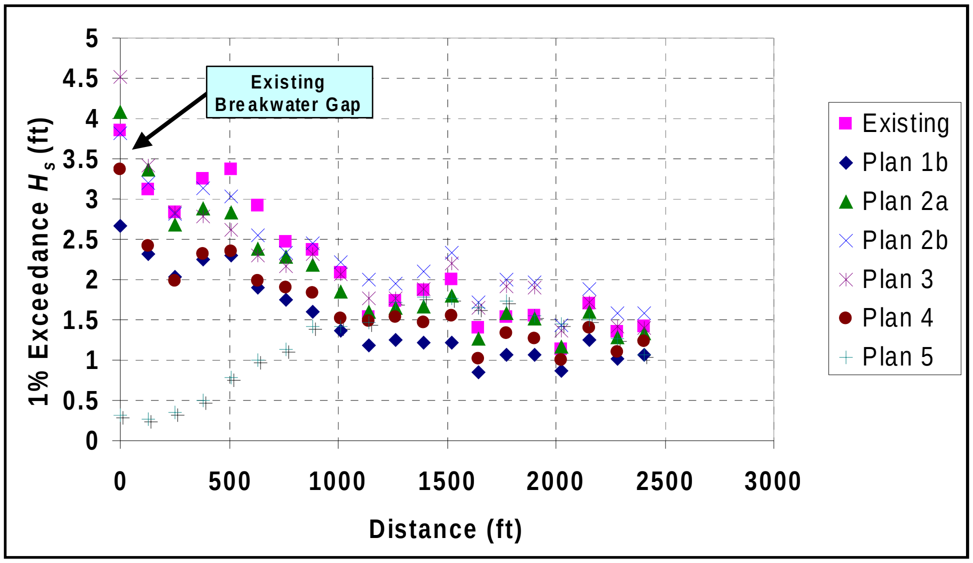

Figure A8. Comparison of H_s exceeded 1 percent of time in harbor mid-basin, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

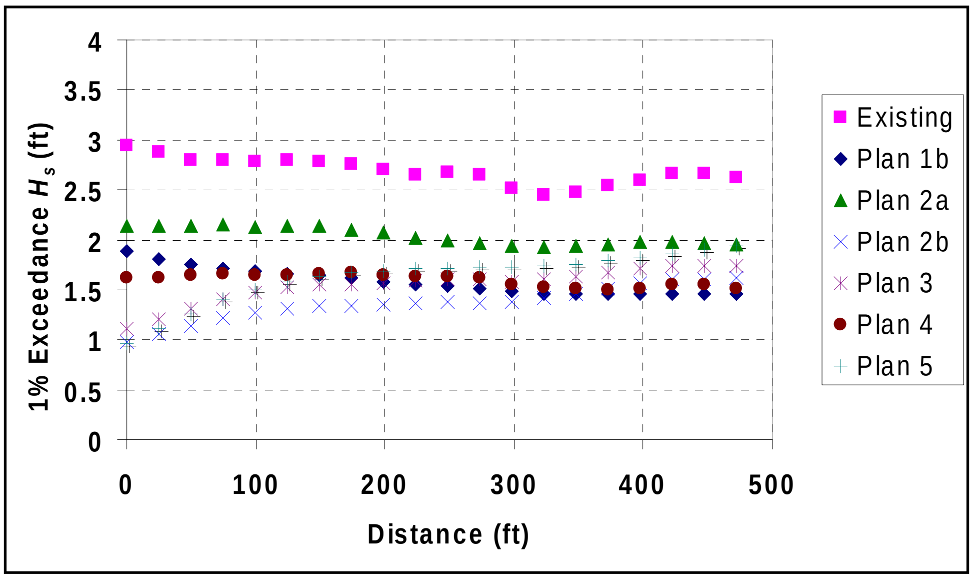

Figure A9. Comparison of H_s exceeded 1 percent of time at barge pier, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

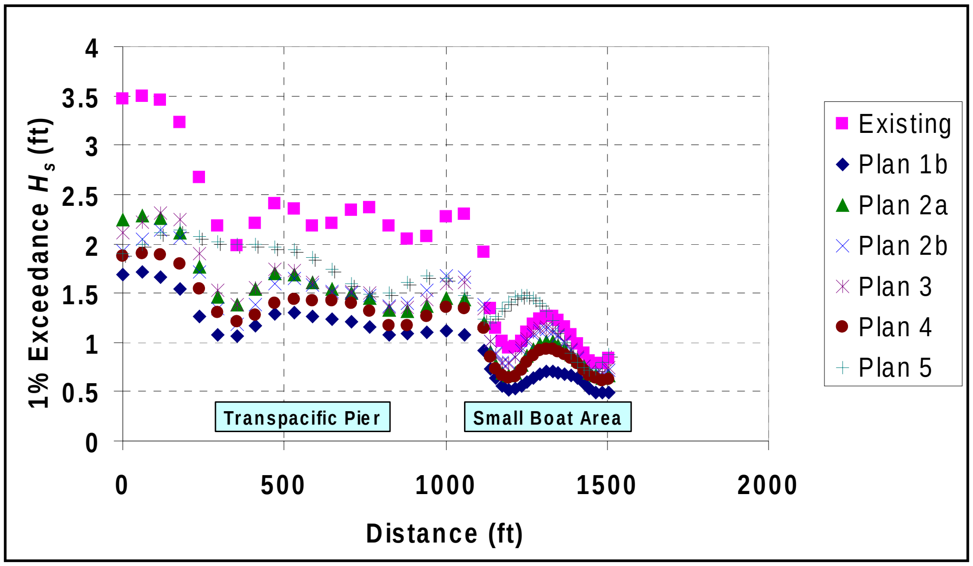

Figure A10. Comparison of H_s exceeded 1 percent of time at Transpacific Pier and small boat area along southeast shore, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

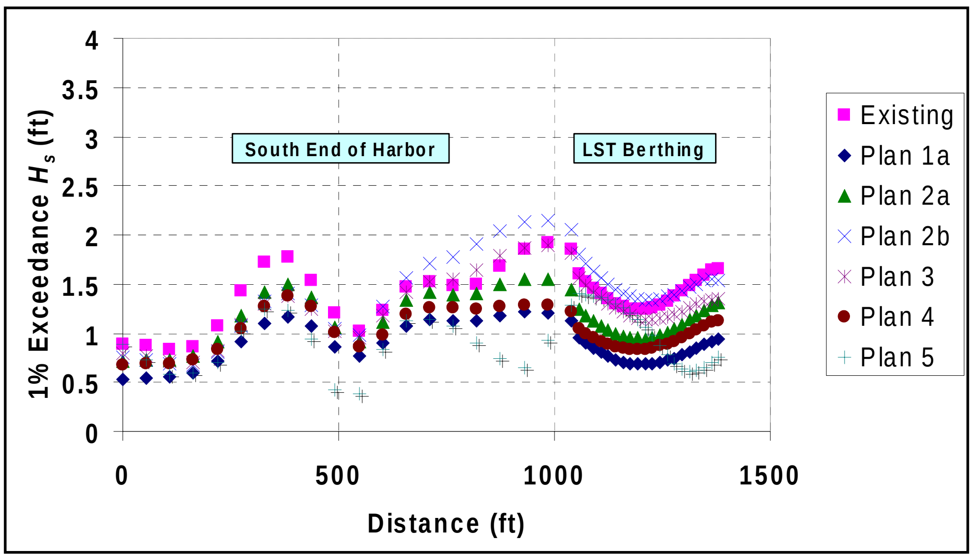

Figure A11. Comparison of H_s exceeded 1 percent of time along south shore of harbor and LST berthing area, existing harbor and Plans 1b, 2a, 2b, 3, 4, and 5

Appendix B
Wave Period and Direction for High Wave Conditions at Commercial Piers

The purpose of this appendix is to provide information about wave period and direction to be expected at the barge pier and Transpacific Pier in Kawaihae Harbor during high wave conditions. This is a supplement to H_s information in the main report.

Corresponding to Table 9 in the main report, the average peak wave period was computed for all observations exceeding the threshold significant wave heights in the existing harbor (Table B1). Thus, for example, for all observations along the barge and Transpacific piers with H_s greater than or equal to 0.3 m (1 ft), the average T_p was 13.1 sec.

Table B1
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, and Corresponding Average Peak Period, Existing Harbor

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Maximum hr	Average T_p sec	Average hr	Maximum hr	Average T_p sec
1.0	1086	1225	13.1	849	1323	13.1
1.5	561	714	13.1	388	870	13.2
2.0	228	326	13.2	179	490	13.5
2.5	101	143	13.6	74	241	13.7
3.0	43	67	13.8	29	130	13.8
3.5	13	36	13.8	13	69	13.8
4.0	1	8	13.8	6	35	13.8
4.5				1	12	13.8
5.0					1	13.9

Figures B1 and B2 give more information about the range and probability of T_p values that can occur during high wave conditions. The model results represent a full year (Figure B1) while the gauge results only represent several months (Figure B2). However, both figures indicate that T_p during high wave conditions generally tends to be in the range 11-15 sec. A notable exception is the 5-7 sec wave periods recorded by the gauge for H_s greater than or equal to 2.1 m (7 ft). These observations were due to local storm events, as discussed in the report. Similar events are included in the 1-yr climate represented in Figure B1, but the percent occurrence is too small for them to appear as a shaded cell.

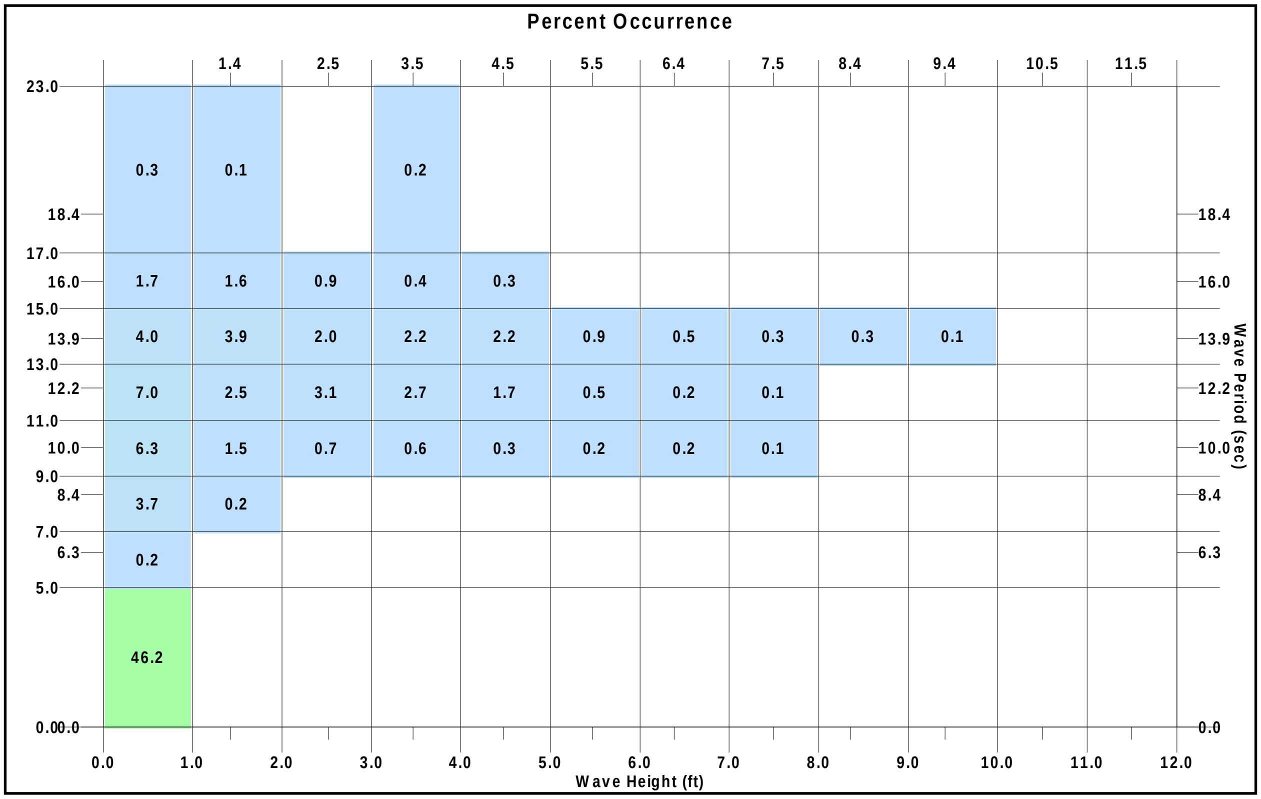

Figure B1. Percent occurrence, T_p vs. H_s , for STWAVE station coincident with Kawaihae outside gauges, Dec 94 – Nov 95, 17-m (55-ft) depth

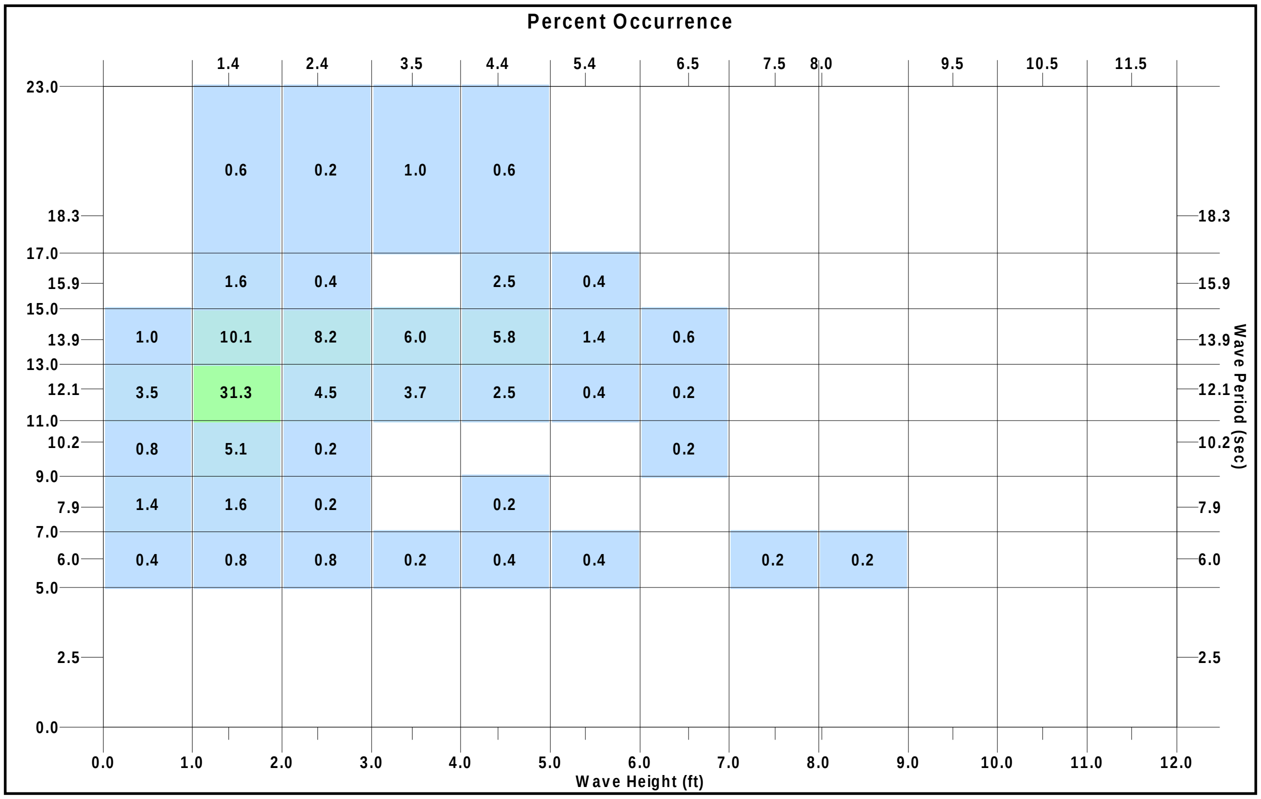

Figure B2. Percent occurrence, T_p vs. H_s , for Kawaihae outside gauge 0388, Jan – Mar 04, 17-m (55-ft) depth

Waves approach the piers from the harbor entrance. There is little wave refraction over the relative flat harbor bottom. Thus, the waves approach each pier approximately from the direction of the harbor entrance. Phase contours from CGWAVE modeling of one case illustrate more clearly (Figure B3). Wave travel direction is perpendicular to the phase contours.

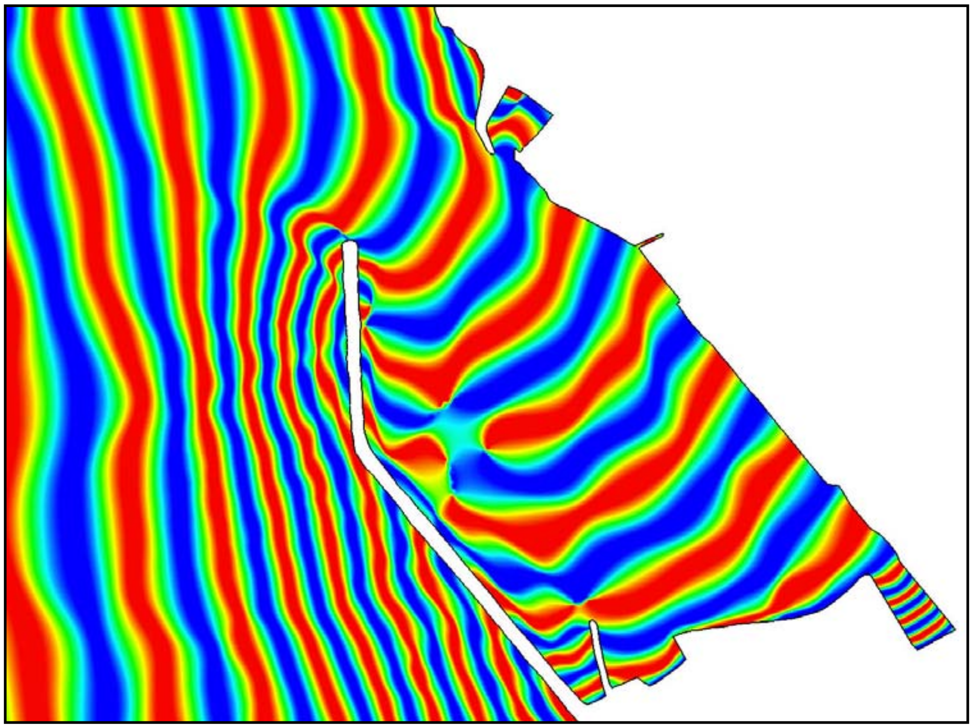

Figure B3. Wave phase contours, existing harbor, T = 14 sec, wave direction = 270 deg azimuth

With the exception of Plan 5, wave periods and directions in the plan harbors can be expected to be similar to those for the existing harbor, since waves approach the piers through approximately the same entrance. Separate results are provided for Plan 5 because of the radical relocation of the entrance in that plan (Table B2 and Figure B4). The average T_p along the piers in Plan 5 is 13-14 sec, as with the existing harbor, except for the highest wave cases along the Transpacific Pier. For these cases, with H_s greater than or equal to 0.9 m (3 ft), the average T_p was 5.8 – 8.0 sec. These cases can be attributed to the effect of local storm events such as those recorded by the gauges during Jan-Mar 04. The direction of wave approach to the piers in Plan 5 is about 90° different from the other harbor configurations (Figure B4). Waves in Plan 5 approach perpendicular to the pier alignment.

Table B2
Significant Wave Height Exceedance Along Commercial Piers, Number of Hours per Year, and Corresponding Average Peak Period, Plan 5

H_s ft	Barge Pier			Transpacific Pier		
	Average hr	Maximum hr	Average T_p sec	Average hr	Maximum hr	Average T_p sec
1.0	534	796	13.2	652	886	13.0
1.5	125	250	13.5	175	291	13.2
2.0	30	62	13.8	47	88	13.3
2.5	5	18	13.9	8	19	13.2
3.0					2	8.0
3.5					1	5.8

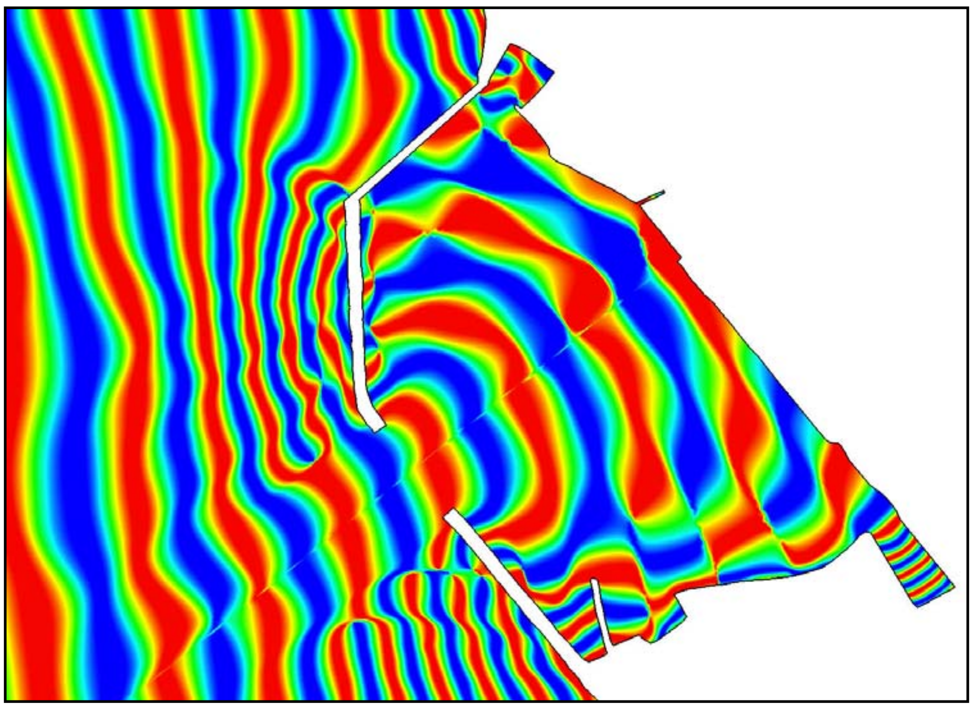

Figure B4. Wave phase contours, Plan 5, T = 14 sec, wave direction = 270 deg azimuth

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14. ABSTRACT

Present and projected commercial activities in Kawaihae Deep Draft Harbor, Island of Hawaii, HI, indicate that a deeper basin and entrance channel and better protected berthing areas will be needed. The U.S. Army Engineer District, Honolulu, in coordination with the Harbors Division, Department of Transportation, State of Hawaii, requested numerical (computer) model studies in support of harbor planning. Wave climate incident to Kawaihae Deep Draft Harbor was developed from National Data Buoy Center directional buoy data. Numerical model STWAVE was used to modify the buoy data to account for significant differences in exposure between Kawaihae and the buoy locations. Numerical model CGWAVE, validated with field measurements for short waves (wind waves and swell), was used to: 1) evaluate the impact of deepening the existing harbor, which was found to be minimal; 2) determine optimum length for a proposed stub extending seaward parallel to the existing entrance channel from the tip of the existing breakwater; and 3) evaluate the technical feasibility of six alternative modifications to the harbor. Model results were compared to experience in the existing harbor and to general criteria for operational acceptability.

15. SUBJECT TERMS

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Kawaihae Harbor	Wave climate
	Wind waves and swell

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